STATIONARY TYPE SLOW SPEED ALTERNATING CURRENT GENERATOR DESIGN

BY

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PREFACE

This paper is a treatise upon the elements of the design problem faced when a set of specifications are placed before a designer. It does not attempt to go into elaborate detail as the why and wherefore of each individual step of the design, but rather treats the problem as a general exploration of the more important steps to be reasoned with in the design of a particular machine.

The general procedure followed is one which covers first, what the designer confronts, what the specifications require, what the results of his calculations are, the investigation of some of the more fundamental theories behind the reasoning, the general requirements of a regulation and field excitation system for the specification, and finally, a general over-all physical picture of the end result. The basic calculations appear in the appendix of this paper.

Obviously, much information has been drawn from the literature dealing with the subject, for which credit is given as the paper develops. The author is also indebted to these professors of the Electrical Department of the Naval Postgraduate School: Professors C. V. O. Terwilliger, W. C. Smith, and E. E. Vivell.

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SYMBOLS AND ABBREVIATIONS

SYMBOLS

$\longrightarrow$	-	Vector Voltage.
$\rightarrowtriangle$	-	Vector Amperes.
$\multimap$	-	Vector Flux, or Vector Ampere-turns.
Δ	-	Peripheral current density.
%	-	Percentum.
Φ	-	Flux density, or flux.
/	-	Typist slant bar - ratio, - or dividing symbol.
@	-	Measured at.

ABBREVIATIONS

A	-	Area of cross section
AIEE	-	American Institute of Electrical Engineers
ASA	-	American Standards Association.
ASTM	-	American Society of Testing Materials.
AT	-	Ampere turns, (NI)
AWG	-	American Wire Gage
B	-	Magnetic flux density, gausses or lines per sq cm.
CFM	-	Cubic feet per minute
circ.	-	circular (mil)
cm.	-	centimeter
cps	-	cycles per second
DC	-	Direct current
DCC	-	Double cotton covered
D^2L	-	Armature diameter^2 x armature length
ea.	-	each, or per
F	-	Force, or Field

SYMBOLS AND ABBREVIATIONS
(Cont.)

ABBREVIATIONS (Continued)

fpm - Feet per minute

fps - Feet per second

HP - Horsepower

I - Current, amperes

ins. - Inches

JPI - Joint (Army-Navy-Air Force) Packing Instructions.

KVA - Kilovolt-amperes

KW - Kilowatts

l - length, armature, inches, pole, etc., sometimes written ℓ

lbs. - Mass or force, pounds

max. - maximum

mmf - magnetomotive force

NEMA - National Electrical Manufacturers Association.

NL - No load

°C. - Degrees, Centigrade scale

°F. - Degrees, Fahrenheit scale

PF - Power factor

psi - pounds per sq. inch

R - Resistance

RPM - Revolutions per minute

SAE - Society of Automotive Engineers

SC - Short circuit

SCR - Short circuit rating, regulation

X - Reactance

I - INTRODUCTION - THE BASIC DESIGN PROBLEM

The basic design problem facing the electrical machinery designer follows along these general lines. He is faced with the questions of HOW?, WHERE?, WHAT?, WHEN? and WHY? He aligns the problem along these bounds. We shall present it here in the form of three questions with outlined answers to avoid a lengthy dissertation readily available to all designers in any number of good basic texts. This is our outline:

1. WHAT does the designer start with?
   - (1) Size of Load - HP, or KW, and PF
     - a. Normal loads - Overloads
   - (2) Permissible Temperature Rise
     - a. Armature - field winding - mechanical parts
     - b. How measured in each case?
   - (3) Speed - RPM
     - a. Normal speed - overload speeds.
   - (4) Type of Construction.
     - a. Degree of enclosure - open - drip proof - splash proof - explosion proof - totally enclosed.
     - b. Method of ventilation - self - blowers - hydrogen.
     - c. Method of cooling - heat exchangers - room exhaust.
     - d. Arrangement of bearings.
     - e. Connection to other machinery - type of coupling belts - chain drive - flange sizes.

f. General arrangement - dimension limitations - weight limitations - horizontal mounting - no athwart ship mounting aboard ship.

(5) Requirements of Loads

a. Voltage - under and over - wave shape desired

b. Power factor

c. Efficiency

d. Torques

e. Current - inrush motors

f. Stability - Short Circuit Rating - reactance requirements.

g. Regulation - limits

h. Inertia - spring constant

i. Reactive KVA - line charging

j. Noise

k. Radio and telephone interference

(6) Available Excitation

a. Source - bus - DC exciter - separate driven exciter - electronic - static.

(7) Standards

a. Company handbook and published data.

b. A.S.A.

c. NEMA

d. AIEE

e. ASTM

f. Customer

g. Government

(8) Performance and Inspection

a. Maritime Commission

b. Navy Department - BuShips

c. Army Engineers

d. Army - Navy - Air Force

2. WHAT are the machine limitations?

(1) Regardless of application or design all machines are limited by certain physical laws which in turn arise from materials in the machine. These materials and their limiting criteria are:

a. Iron - flux limitations.

b. Copper - current carrying limitations.

c. Insulation - voltage limitations.

d. Steel - mechanical support problems.

e. Ventilating fluid - temperature rise limits.

(2) Mechanical Limitations

a. Centrifugal forces acting on rims, field poles.

b. Load torque acting on driver.

c. Magnetic forces acting on conductors and iron.

d. Critical speeds in high velocity machines.

e. External shock - gyroscopic action.

(3) Thermal Limitations

a. Insulation - Class A - 105 degrees Centigrade
- Class B - 125 degrees Centigrade
- Class H - 180 degrees Centigrade
- Class C - No limit - silicones

b. Ventilation - free - forced - liquid.

c. Losses - 100 CFM per KW for an 18°C. air temperature rise.

(4) Electrical and Magnetic limitations.

a. Ability to carry current not limited except in heating. Current density varies from 1500 amperes per inch squared to 4000 amp/in^2.

b. Flux - saturation - 120,000 $lines/in.^2$ or 18,000 gauss.

c. Armature current loading limits - delta - Δ

Δ = amperes per sq. in. of armature periphery.

= 1200 for Class A insulation.

= 1800 for Class B insulation.

d. Average air gap density, magnetic, 28 to 30 kilo lines per $inch^2$.

(5) Performance Limitations.

a. Maximum output generator.

1.0 PF - 150%; 0.80 PF - 200%

Increased by - increasing field mmf, by increasing air gap, or by field heating.

b. Generator regulation.

Standard generator - 50°C. rise - 40%

- 40°C. rise - 25%

Increased in same manner as above.

c. Efficiency and heating.

High temperature machine - low efficiency.

Thermal coefficient of copper.

High flux densities - customary densities shown at top of next page.

Magnetic path	60 cps	25cps
armature core	50,000-90,000	80,000-110,000
armature teeth,ave.	80,000-100,000	90,000-110,000
armature teeth,max.	115,000	120,000
air gap	30,000-50,000	30,000-50,000
*pole body	90,000-110,000	90,000-110,000
*spider, max.	120,000	120,000

* dependent upon choice of material.

d. Voltage limitations.

Space factor.

Heating.

Optimum for rating.

Secondary effect of increased Xl, or $X\ell$

e. Power Factor.

PF	KVA/D^2L	PF	KVA/D^2L
1.00	1.000	0.80	0.845
0.90	0.890	0.70	0.803

f. Starting and synchronizing torques.

Three machines in one - induction motor - with three types of rotors - reluctance and synchronous.

g. Torsional vibration.

$WK^2 = P_r =$ torsional rigidity

h. Noise limitations as per specifications

i. Radio and telephonic interference.

3. WHERE does the designer start his design and HOW?

(1) Review of past designs.

(2) Existing tools.

(3) Development of new tools.

(4) Justification of expense.

(5) Types of construction.

a. Armature punchings.

b. Armature coil - drum - nested - multiple turn - bar - taped turns - half back - inverted turns.

c. Rotor poles - solid - bolted - dove tail - lip -

d. Field winding - wire - pole and form wound - strip.

(6) Procedure in design depends upon the individual and starting point, but usually

a. Assume punching diameter and length.

b. Determine armature coil from Area and Φ

c. Check flux capacity.

d. Check armature coil heating.

e. Check SCR

f. Calculate excitation.

g. Design field coil and check field heating.

(7) Efficiencies.

a. Calculate reactances.

b. Calculate starting performance.

c. Check mechanical limitations.

d. Check criticals - lateral and torsional - stresses in pole roots, flywheel rim.

e. Layout mechanical structure.

f. Check mechanical stresses.

g. Make alternate designs.

h. Choose optimum design from all compared.

Thus, the basic design problem resolves into three ideas: - What are the starting conditions? - What are the electrical and physical limitations? - Where does the designer start his design and how?

We came upon our thesis subject while visiting the Coast Guard Yard at Curtis Bay, Maryland. At that time there was undergoing tests an unattended lightship power plant consisting of three self-excited, diesel driven, slow speed, generator sets, to be remotely controlled. This brought to the writer's attention that there was a feasible way besides exciter excitation to supply field power to a generator. To design one such machine became my thesis subject. This paper is part of my effort towards this end.

II - THE SPECIFICATIONS

The specification upon which our machine is based is, in part, as follows. I quote from U.S. Coast Guard Civil Engineering Division Specification 4-B-5 for Stationary Type, Slow Speed, Heavy Duty, Diesel-Engine-Driven Generator Sets, dated August, 1949:

> At this writing, 1 May 1950, the contract has been let in this instance, and delivery of the sets as required will be made sometime during the winter of 1950-1951.
>
> 1. Scope: - This contract will include the furnishing of eight (8) heavy-duty, slow-speed diesel engine driven generators complete with all accessories and spare parts as specified herein. These engine generators will be installed two to a group with all accessories and one switchboard in Coast Guard Loran Stations located in the Western Pacific areas......
>
> 2. General: - The intent of these specifications is to obtain four groups of machinery. Each group will consist of: two slow-speed, air starting, 3-phase, 240-volt, 60-cycle, diesel engine driven generators of not less than 93.8 KVA at 80% power factor; a complete switchboard; instruction books,...and special means of excitation and voltage regulation for each generator, all complete with spares as..........................
>
> 3. Engines: - The diesel engines shall be vertical. designed for continuous service, direct-connected to alternating current generators. The rotative speed shall be not less than 360 nor more than 450 synchronous revolutions per minute (RPM). They shall be capable of starting cold within a temperature range of 20 to 75 degrees Fahrenheit..
>
> 9. Critic Speeds: - Each diesel engine with its direct connected alternating current generator shall be engineered and designed as a complete unit and is to be free from all harmful critical and torsional vibration within the operating range of speed and capacity......
>
> 11. Generator: - The electric generators shall be direct connected to the diesel engines and shall deliver three phase, three wire, 60 cycle, 240-volt alternating current voltage at rated engine speed. The generators shall have a continuous duty rating of not less than 93.75 KVA at 80% power factor. They shall be of a recognized standard make and shall be built in accordance

with the latest standards of the AIEE and NEMA. The generators shall be capable of delivering electrical energy continuously at their full KVA rating without exceeding a temperature rise of 60 degrees Centigrade in the stator of the field windings for Class A insulation in an ambient temperature of 40 degrees Centigrade, when measured by the rise in resistance or by imbedded detectors. Generators shall have low reactance field circuits capable of fast response to field current changes.

(a) Excitation: - Main field static excitation is required. No restriction exists as to method other than as specified herein. Electronic devices will not be acceptable if their failure will result in loss of excitation. The equipment and method used must be reliable and guaranteed by the manufacturer.

(b) Voltage regulation: - Steady state voltage regulation as defined by the A.S.A., shall not be more than 3% at rated power factor. Short time voltage dips or surges due to any change in the alternating current line current (not to exceed 100% rated current) and reactance of generator field and characteristics of automatic voltage regulator shall not exceed 10% plus or minus, and shall have decayed to steady state in not more than one-half second. Better performance is desired and will be evaluated....... The voltage regulation equipment must be completely static, and may be incorporated in the excitation equipment. Electronic devices will not be accepted if their failure will result in the loss of excitation. The voltage regulation equipment shall be furnished with means for manual adjustment of voltage. Cross connections between the voltage regulation equipment will be permitted for parallel operation of generators.

(c) Parallel operation: - The governors, generators, excitation and voltage regulation equipment shall be designed and guaranteed for satisfactory parallel operation of two generators under any load condition. Semi-automatic paralleling by manual closure of oncoming generator breaker with delayed field excitation is required. Provision shall be made on each generator panel for momentary excitation to permit adjustments of speed and voltage prior to paralleling. Under conditions of parallel operation each generator shall carry (within 5%) one-half the total load on the system.

(d) Phase Unbalance: - Under a condition of single phase load of 15% of rated amperes at any power factor between rated and unity and with no other load on the generator, the var-

iation in voltage between phases shall not exceed 5% of rated voltage.
(e) Short Circuit: - Generators shall be capable of withstanding without injury to any part, a three-phase short circuit at the terminals for a period of two minutes with constant field excitation. The generator shall also be capable of withstanding a single-phase short circuit between any two terminals for a period of two minutes with constant field excitation.
(f) Protection Against Corrosion: - In order to prevent deterioration due to corrosion, all bolts, studs, pins, springs, screws, cap screws, and other such fastenings or fittings, shall be of a satisfactory corrosion-resistant material or of a material treated in a satisfactory manner to render it adequately resistant to corrosion.
(g) Audio Noises: - Generators shall operate without objectionable audio noise at all loads and speeds within the service range.
(h) Insulation Resistance: - The insulation resistance of the generator stator and field windings, when corrected to 25°C., shall be not less than 25 megohms if Class A insulation is used and not less than 50 megohms if Class B insulation is used. Correction for temperature shall be made on the basis of insulation resistance doubling for each 15°C. decrease in temperature. This test shall be made on the completed generator and it shall be made before the dielectric strength test is made.

18. Packing and Shipping: - Upon acceptance, all equipment and parts subject to damage by salt water or rainfall shall be prepared and packed for overseas shipment in accordance with JPI-14A. This applies particularly to electrical items.........The engines and generators shall be disassembled and packed in the smallest practicable shipping units; packages shall not exceed 5000 pounds gross weight.

The specifications read thus. We shall now proceed with the design calculations and show next the results electrically of these calculations.

III - THE ELEMENTS OF THE FINISHED MACHINE

This Chapter is best expressed as a tabulated presentation of the results of the calculations of Appendix A, there being only descriptive terms and numerical values of interest to the planning section of the manufacturer in these figures. This table, upon being sent to the estimators and planners of a manufacturer, will be scrutinized and made to fit a similar design of the company unless there is an altogether new idea in the design. Certain patent rights and uses come into the picture at this point, and there can be no infringement by the one company upon the patent rights of another. All ideas, we are advised, are fair game for the thesis investigator of a Naval or other Government school, in that the United States Government has free access to the patents of all concerned when such an investigation is being made. If the designer were to put his design into the open market for competitive purposes with those of other designers, then by law he must conform to those patent rights to which he has access, and must not infringe upon the rights of others.

The tabled results are as follows:

Salient pole machine design sheet.

Armature - (stator)

Bore punchings		- 0.014	ins.
Core width		- 4.7	ins.
Air ducts, No. and width	One	- 0.5	ins.
Depth below slots		- 4.0	ins.

Frame yoke bore -	- 42.5 ins.
Segments, - (quadrants) -	90 degree
Type winding - lap - 5/6ths pitch - 6 φ inside - series	
Chord factor -	0.833
Throw -	4.22 ins.
Conductors per slot -	4 ea.
Total conductors -	480 ea.
Size conductors -	0.185 x 0.956 ins.
Current density -	1145 amperes per inch squared
Total flux - Φ	716,541 lines
Section air gap -	22.2 inches squared per hole
Gap density -	32245 lines/inch squared
Leakage constant (accounted for) -	1.175 to 1.18
Flux per pole -	38,000 lines/inch squared
Tooth pitch -	0.79 ins.
Tooth density -	118,000 lines per inch squared
Core density -	23,700 lines per inch squared
Weight volume of teeth - 420 cubic inches -	118 lbs.
Weight volume of core - 1830 cubic inches -	512 lbs.
Grade of iron - 2.3 Si. -	0.014 inches thick
Loss in teeth -	1065 watts
Loss in core -	300 watts
P.F., Damper, and End losses -	340 watts
Total Iron losses -	1705 watts
One-half mean turn -	4.7 ins.
Ventilation -	natural
Resistance per phase @ 75°C. -	0.008 ohms

Armature I^2R loss @ 75°C. -	1205 watts

Field - (Rotor)(Salient Pole)

Total air gap at center of field pole -	0.25 ins.
Diameter of rotor at center line of field pole -	29.65 ins.
Peripheral speed -	47.343 f.p.s. - 2840 f.p.m.
Pole pitch -	4.65 ins.
Section pole -	1.5 x 3.0 ins. - 4.5 inches square
Pole density -	38,000 lines per square inch
Spider section -	1.0 x 4.56 ins. - 4.56 square inch section.
Spider density -	75,000 lines per inch squared - forged steel
Type spider -	forged steel fabricated by welding.
Damper slot pitch -	0.375 ins.
Damper bars -	No. 10 A.W.G. - round - 0.102 ins. diameter
Damper end ring -	continuous - copper - 0.25 x 0.25 at 29 inch diameter
Effective air gap -	0.25 ins.
Turns per pole -	240
Size copper -	No. 13 A.W.G.
Size copper -	0.084 inch diameter D.C.C.
Mean turn length -	11.4 ins.
Surface area -	76.0 sq.ins.

C - OVERALL PICTURE

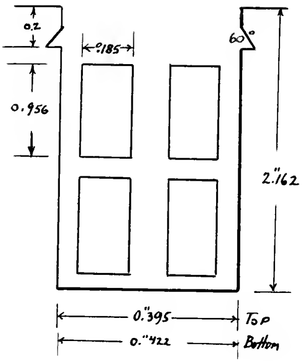
K.V.A. -	93.75
P.F. -	0.80 lagging
Amps -	10.5 field amperes
Resistance -	0.505 ohms at 60°C.
IR -	5.6 volts
I^2R -	55 watts

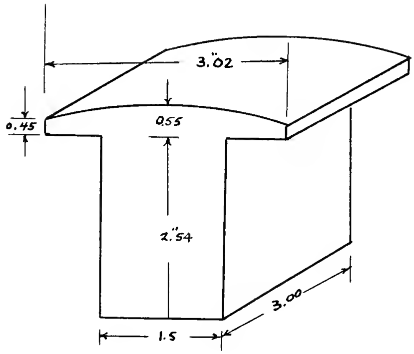
Sq. Inches per watt - 1.38

Excitation Capacity Calculated - 5 volts, 10 amperes per pole

Weight of armature copper - 300 lbs.

Weight of field copper - 150 lbs.





Efficiency at full load - 93.0% at PF 0.80 lagging.

load	25%	50%	75%	100%	125%
Armature I	56.40	112.75	169.15	225.50	281.90
Field I	10.50	10.50	10.50	10.50	10.50
Field volts	100.00	100.00	100.00	100.00	100.00
F & W losses 1500					
Core losses 1696					
Arma. I^2R	80.00	320.00	715.00	1275.00	1990.00
Field Loss (120 x 10.5) 1260					
Total losses	4540.00	4680.00	5095.00	5655.00	6370.00
Efficiency	81.00	89.00	91.80	93.00	93.75%

Summary of results:

93.75 KVA @ 0.80 PF - 240 volts - 225.5 amps - 3 phase -

60 cps - 360 RPM - 20 poles - salient field poles design -

natural ventilation with 48 degree rise - 60 degree rise allowable as per the specification. The machine at this point, appears to be contained in an area 43" diameter, 9" long axially.

IV - THE FUNDAMENTAL PRINCIPLES

The problem constantly before the designer is how to build the machine which will economically fulfill the specification. To meet the specifications, it is well for the designer to recall that there are certain matters which are common to all generators, motors and convertors, magnetic circuitry, electric circuitry, insulation, ventilation, and the framework of his machine. These certain matters are in the nature of formulae and details of shop practices.

All dynamo-electric machines depend upon the same fundamental facts for their operation: - firstly, the fact that when a conductor is moved across a magnetic field there is generated in it an electromotive force; and secondly, the fact that when an electric current flows in a conductor which itself is in a magnetic field, the conductor is subject to a mechanical force. The questions then arise, therefore, along the following lines: How much magnetic field do we require? How much motion? How much voltage to be generated? How much current? How much force? How to keep heat losses to a minimum? It must not be supposed that the rules enumerated in the reference volumes must be followed to the letter in each instance of design, for if such were to be the case, each designer would in his life span be capable of putting into the hands of his construction personnel but three or four sets of electrical plans. A busy designer would never get through his work if he stopped to calculate everything. He judiciously guesses a good deal of the time, makes rapid estimating calcu-

lations of quantities he has not time to calculate. However, he is not justified in so estimating unless he knows the limit of his possible error with fair accuracy, and knows that with the error he will still have a machine which will comply with its specification. Knowledge of these things can only come from many calculations made and many machines tested. The way to acquire the art of intelligent estimation is to employ fairly simple rules for calculation that are based on sound principles.

Thus for our machine, we shall have to outline the procedure to follow in the problem of producing a machine to meet the specification. We shall have the benefit of all the prior work done in calculating the various performances, both magnetically and mechanically, of the available metals to use in the various parts of the machine. We shall have the background gained by years of experience in the field of those designers and professors who have seen fit to produce their efforts to paper for the benefit of others. We shall not be infringing upon wholly unknown ground when we go into various references for verifications of our estimates and assumptions. We shall follow along the paths of those who before us have had faced the same type of problem.

To establish the overall picture let us examine just what we face. The majority of alternating-current generators are built with a revolving field consisting of a circular rim, to which are attached definite pole pieces projecting outward radially, each pole piece having its own exciting winding in the form of a coil surrounding the body of the pole piece.

The revolving field is surrounded peripherally by the stationary armature, or stator, which carries the armature winding in slots. This is the type in which we are interested. The single phase generator is usually about 30% heavier and more costly than a polyphase generator of the same rating. However by changing the internal armature connections, a polyphase machine may be frequently reconnected to be a three-, two-, or single-phase machine. Transmission costs control the phase ratings of most power machines, and they are most commonly three-phase in character. Two-phase and three-phase generators of the same capacity are practically the same dimension, weight, and cost.

For years there were attempts made to develop a satisfactory and simple self-excited alternator. German patents as early as the latter part of the last century devised and explained systems involving electric conversion of output voltages and current to produce self-excitation. Precedence of English and Swedish competition in the construction field gave little encouragement to this idea. During the 1930-1940 decade the increasing usefulness of the mechanical selenium rectifier gave rise to a more sound reason for the re-emergence of the self-excited machines. German patents, though, stifled development in the United States, until the early 1940's, when just as the last war broke out, renewed interest for alternator simplification reopened the excitation and inherent regulation plans. The perfection of the automatic voltage regulator along with metallic thyratron tubes for

converted power purposes aided the development of this renewed trend. Combining rigid self-regulation with self-excitation is the problem we face with our specifications, and we shall discuss our system in Chapter VII.

Excitation must of necessity, if a machine is a separately excited installation, be from a standardized 125 or 250 volts, D.C. bus. There may be one exciter, (the direct current generator supplying the field excitation voltage), for several alternators, or there may be an individual exciter for each alternator, and the individual exciter may be on the same shaft with the prime mover and alternator.

All alternators are rated in kilovolt-amperes, and unless otherwise specifically stated, are rated at that KVA which they will give continuously without a rise in temperature exceeding certain insulation-limit predetermined values.

Inorganic insulating materials allow a temperature rise greater than organic materials such as cotton, impregnated cotton, and varnish impregnated materials. The latter are used in the armatures of most slow- and moderate-speed machines.

Most machines have their fields designed sufficiently liberally to enable them to give their rated power at 80 per cent power factor with rated voltage. This is the case of our specification, also. The heating of the armature depends upon the KVA load, not the KW load, for the KVA load expresses the actual rated volts and amperes which cause the heat losses. The lower the power factor of the inductive load

connected to the alternator, the greater the heating of the field coils for the same KVA output. This can best be seen by a cursory inspection of the vector diagram which shows no-load and terminal volts, along with the flux representations which indicate the ampere turns required of the field coils to produce the required flux in the alternator in producing its rated output at the lower power factor loadings.

The principal parts of the alternator are:

(1) The stator frame, which is usually of cast or forged steel in a box or hollow form. It is the mechanical structure of the machine serving to support the stator. It is usually made hollow and thus aids in directing the ventilating air.

(2) The stator core is the ring of laminated steel with slots on its inner race for the armature copper conductors. The core is usually made up of sheets of 0.014 inch steel, punched in sectors of a circle with the joints staggered as these laminations are piled up in layers.

(3) The armature winding may be single-phase, two-phase, or three-phase, externally. The latter is most common, while the added arrangement of making the winding what is termed six-phases-inside, that is, arranged to give three sets of paired windings under the influence of the revolving generating field flux, is sometimes employed to derive a greater output with the same amount of copper. This is gained because the correction factor for the conductor spacing with relation to each other is greater for the six-phase-inside case and therefore there is the gain desired. The winding

consists of form-wound coils placed in slots and connected up in accordance with the Figures 1 and 15. The coils are insulated with varnish, varnished cambric, cotton or linen, and taped for mechanical binding. Ours are going to be varnished, and we shall use pressboard for separating the copper from the steel laminations themselves.

(4) The field poles are usually laminated steel punched 0.025 to 0.075 inches thick with flaring poles shoes. They are usually of rectangular cross-section and bolted to the rim, thus holding the field coil in place. The pole face is beveled, champered, or otherwise machined to give the flux wave the desired shape.

(5) The field coils consist of many turns of wire, or copper ribbon wound on edge, with insulation between turns. All spools are connected in series and designed so that the specified exciter voltage will give the required field current plus a slight margin for emergencies.

(6) The field yoke is either cast or forged steel, whichever suits the economy of the design, and is in the form of a rectangularly sectioned ring or rim of reasonable magnetic qualities, as it forms the yoke of each magnetic circuit. It must have ample strength to stand the centrifugal force of carrying the poles revolving at the rated r.p.m.

(7) Collector rings, of which two are required, are placed on the shaft and are required to carry the excitation current to the revolving field coils. Metal graphite brushes resting on the rings form the connecting link.

Three phase - six phases inside - 120 slots - 4 conductors/slot

2 conductors per coil - 20 poles - 6 slots per pole - 120 slots

five-sixths pitch

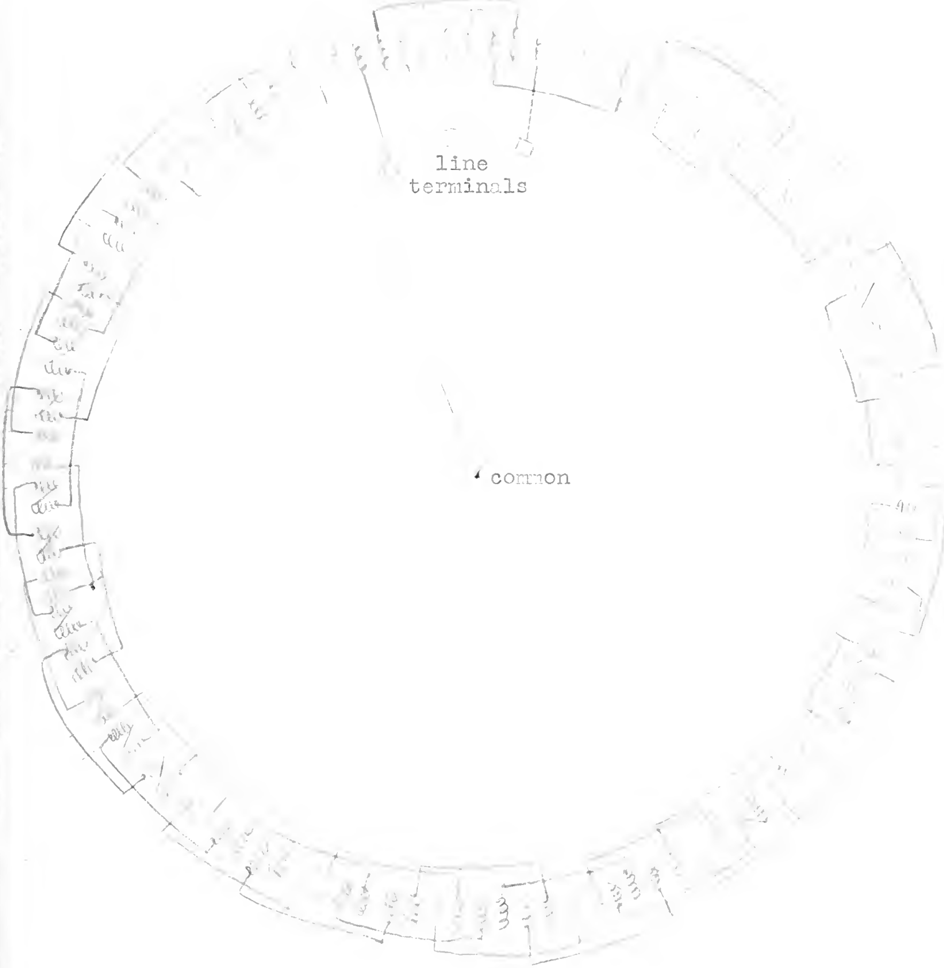


Figure 1

(8) The spider, shaft, bearings, pedestal, and bed-plate are the usual mechanical accessories required for the completion of the assembly.

Thus we have the general picture of what we are striving to design. We shall now proceed with a short relation of the principles behind the circuitry and calculations.

V - MAGNETIC CIRCUITRY - WINDINGS - VENTILATION

1. The Magnetic Circuit

The magnetic circuit includes the field yoke, field poles, pole shoes, air gap, armature laminations, slot copper, and armature yoke. For each of these parts, (except the air gap), it is necessary to choose materials that have suitable magnetic properties. The various materials have properties as follows: Cast steel, which we shall use in the spider of the field yoke, has a saturation curve, for a representative grade of present day available steel, as found in Figure 2. For mechanical purposes it may be operated at a tensile stress up to 16,000 p.s.i. Its weight is figured on the basis of 0.28 pounds per cubic inch. In the spider of high speed revolving field alternators, the metal has to withstand the centrifugal force, and therefore the mechanical stresses must be as carefully investigated as are the magnetic conditions.

Forged steel we shall use in the revolving field pole structure base ring. It has excellent mechanical properties, although in our case where it is to be welded together after forming of the rim, the welded section must be heat-treated to above the austenitic range in order to stress relieve the faults resulting from the welding. Forged steel has very good magnetic permeability. The magnetic properties of a typical grade of forged steel are shown in Figure 3. The maximum working stress is 16,000 p.s.i. This is very important as the proportioning of the revolving structure to withstand

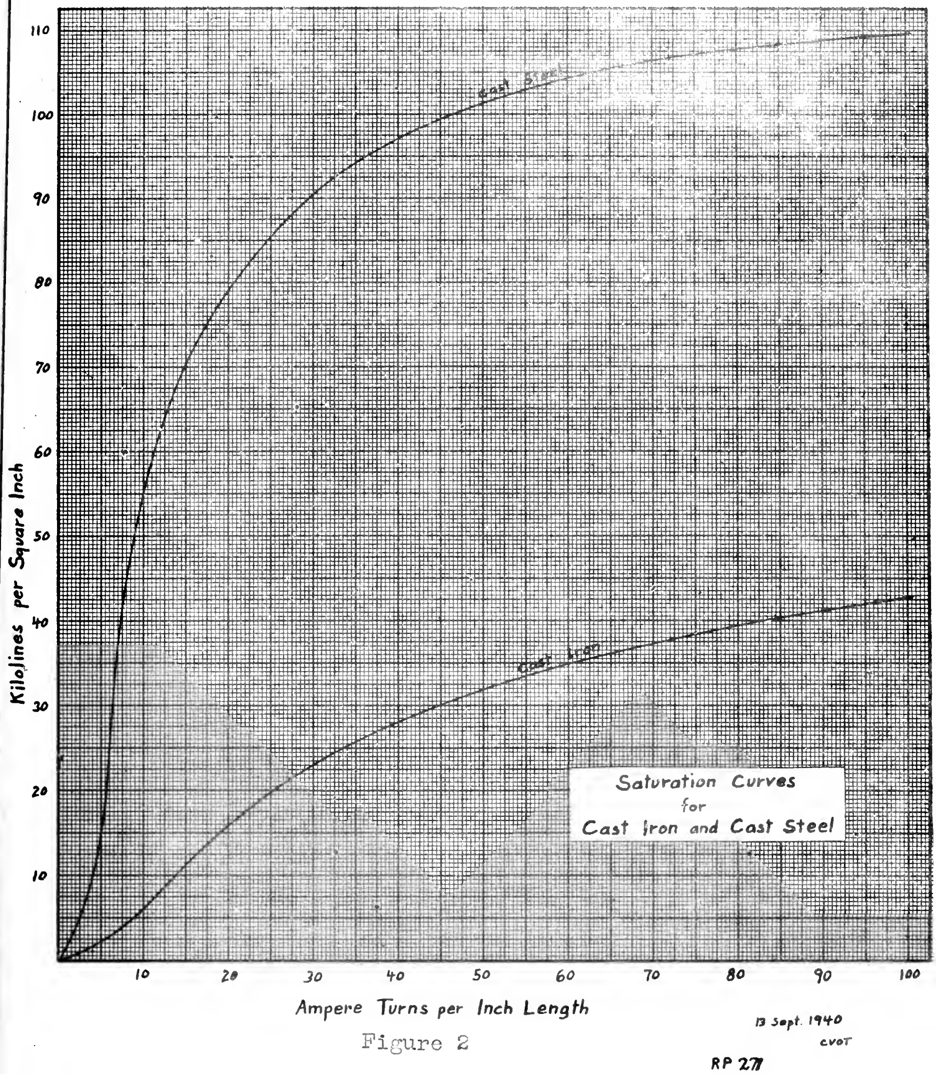

Saturation Curves
for
Cast Iron and Cast Steel
Cast Steel
Cast Iron
Kilolines per Square Inch
Ampere Turns per Inch Length
110
100
90
80
70
60
50
40
30
20
10
10
20
30
40
50
60
70
80
90
100
13 Sept. 1940
CVOT
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Figure 2

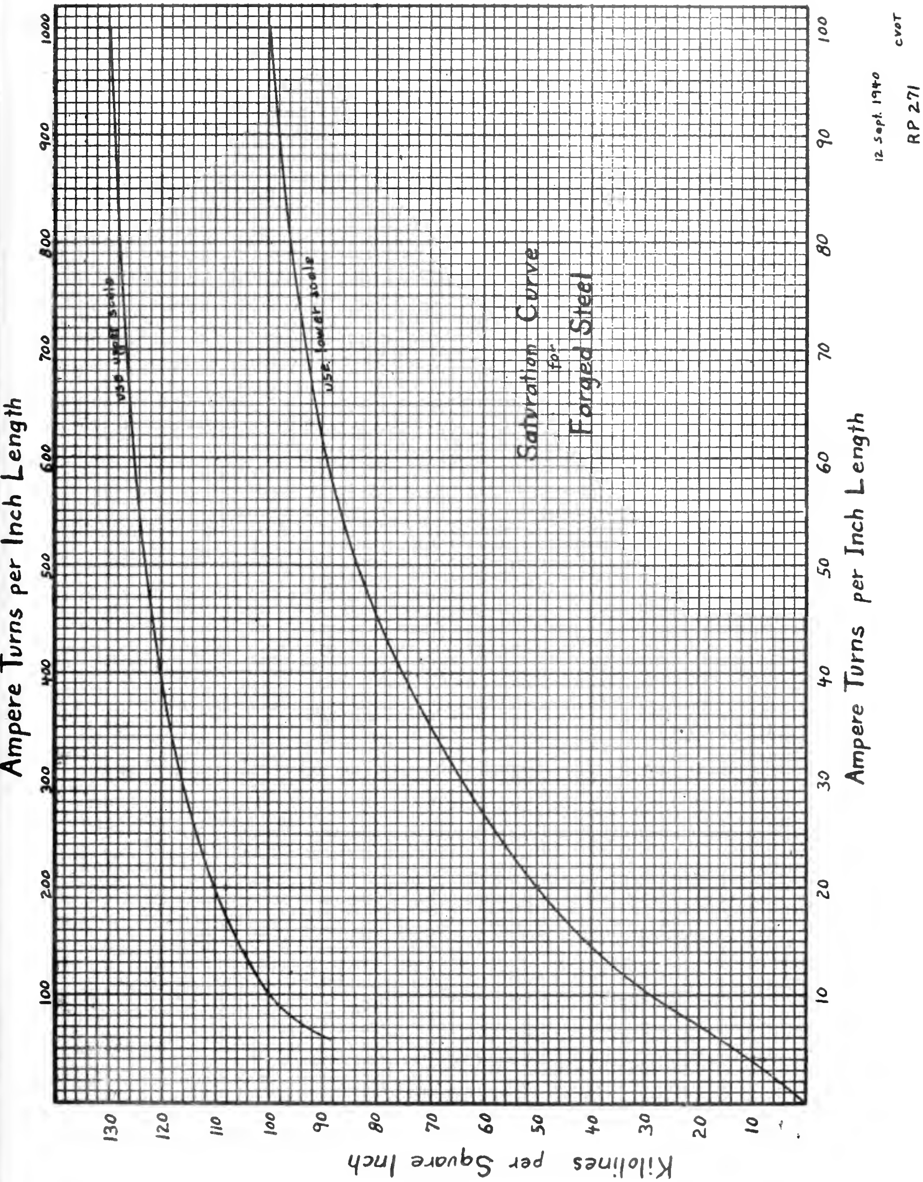
Ampere Turns per Inch Length
Saturation Curve for Forged Steel
use upper scale
use lower scale
Ampere Turns per Inch Length
Kilolines per Square Inch
12 Sept. 1940 CVOT
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Fig. 3

the great centrifugal forces due to the high peripheral velocities is one of the controlling features in the design. The weight of forged steel is also taken as 0.28 pounds per cubic inch.

Laminated steel punchings are used for the armature core and teeth, and for the pole pieces of our machine. The armature laminations will be a 1.0 Silicon steel 0.014 inches thick. See Figure 4. The pole pieces shall be made up of the same quality steel but shall be 0.0633 inches thick. This material is used by Westinghouse Electric Corporation in their smaller machine and is identified as their No. 9112 pole piece stock, Figure 5.

Silicon content controls the hysteresis and eddy current losses of a section of lamination; the higher the silicon content, the lower these losses. The higher the silicon content the lower the permeability, but in an over-all balance of the material, the lower the losses the better the design, and so we shall find that the major manufacturers are using a lamination grade with greater than 1.0% silicon content.

In the magnetic circuit of a machine there are two major losses which come into play to affect the over-all picture. These are the hysteresis and eddy current losses. The hysteresis loss is expressed in watts per cubic inch for one cycle per second at various flux densities and any thickness of sheet. Total loss then can be calculated by taking the basic loss and multiplying it by the total cubic volume and frequency. In the same manner the eddy current losses are expressed in watts per cubic inch for one cycle per second at various den-

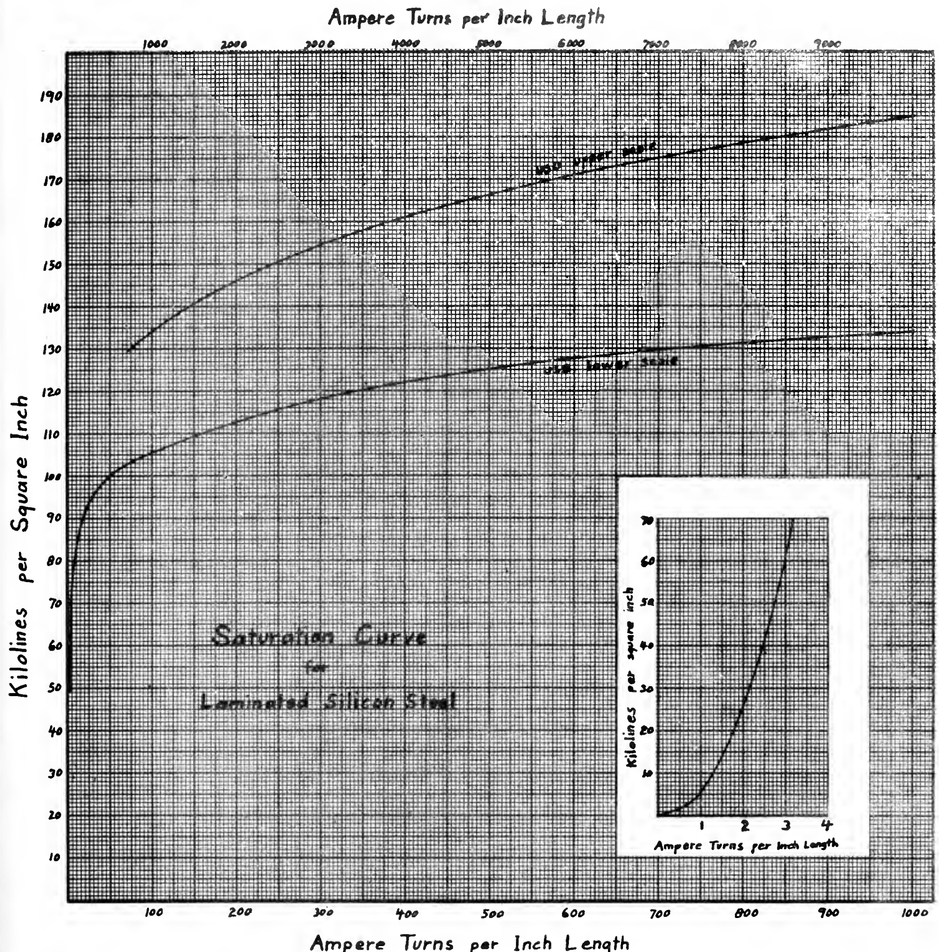

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Fig. 4

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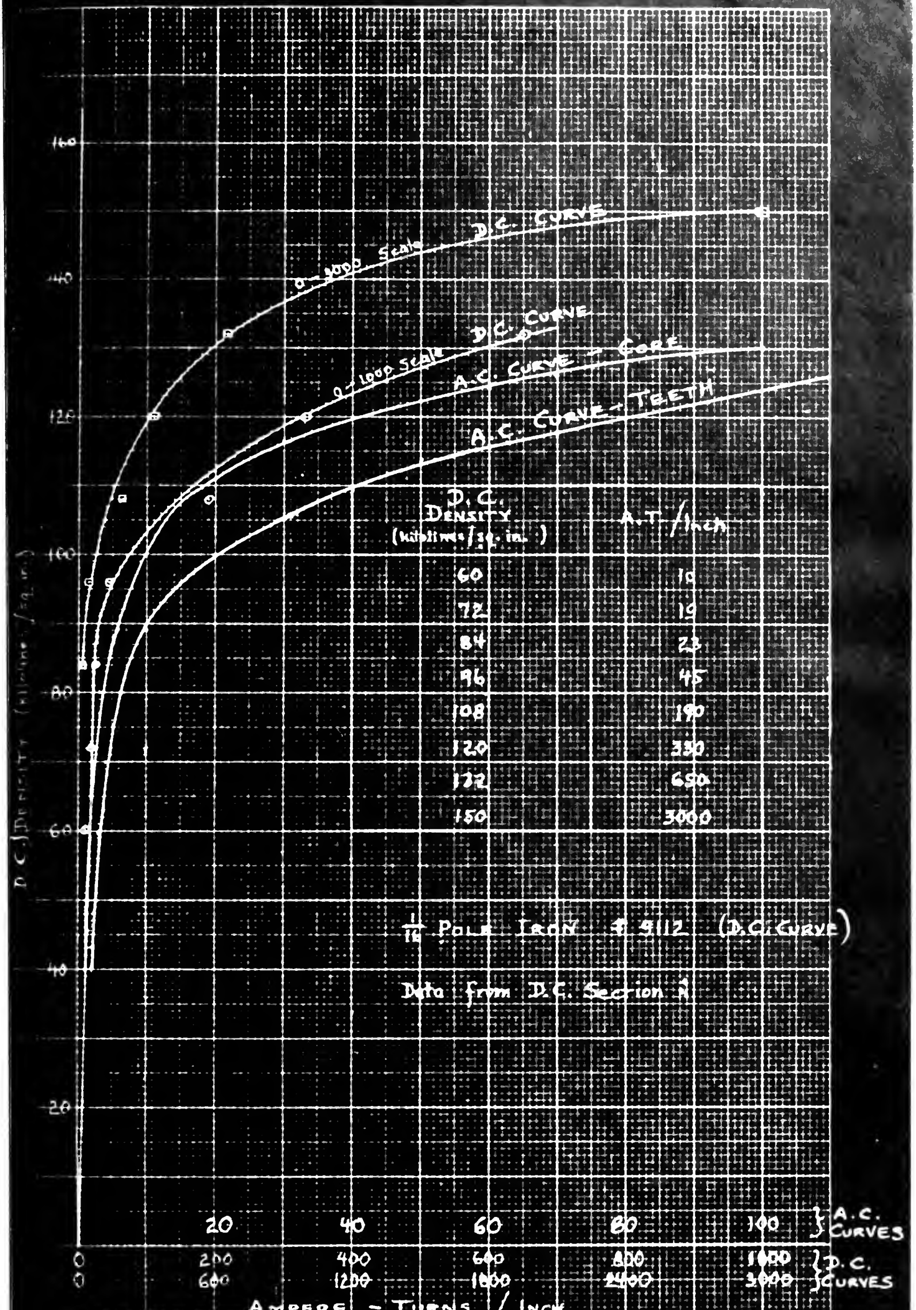


FIG. 5

a Jokl DATE July 23, 1948 CURVE NO.

sities and for a standard thickness of lamination. The total loss then becomes the basic loss and multiplying it by the volume in cubic inches and by the square of the frequency.

The hysteresis and eddy current loss expressions we shall use are based upon the use of 0.014 inch thick, 2.3 Silicon steel laminations, and are as follows:

Hysteresis loss in watts $= K \times V \times f \times B^{1.6}$

where K is a constant $= 5.25 \times 10^{-8}$

V - volume of the steel section in cubic inches

f - frequency in c.p.s.

B - magnetic density in kilolines per square inches.

Eddy current loss in watts $= K \times V \times (tfB)^2$

where K is a constant $= 254 \times 10^{-8}$

V - as before

f - as before

B - as before

t - thickness of lamination in inches.

2. The Electric circuit

The electric circuit consists of the armature windings and the field windings. These consist of in our case flat armature conductors adaptable to ease of forming, insulating, and inserting in the armature slots. The field windings are form-wound No. 13 A.W.G. wire, round in section, and pre-wound over dummy poles mechanically for ease and lowered production costs. The use of these form-wound coils is almost universal at the present time and about the only exceptions are the very small fractional horse power motors

where the windings are sometimes wound directly on the rotors or into the armature slots.

The flat armature conductor is used to get the maximum amount of copper into the small armature slot and thus reduce the I^2R loss of the whole machine.

It is evident that the waste space between the round wires is greater than between rectangular wires packed together. We do not have a machine of such size that there is reason to increase the cost of the pole structures by flattening the pole coil wires to conserve space. The added cost of additional forming of the field pole wire by flattening and winding on the pole form is not justified when there are only twenty poles per machine, eight machines to be built. It is feasible in the armature slot case since there is need of keeping the losses down and to conserve space so that the slot proportions shall be within structural and magnetic reason and still have the minimum number of slots per pole per phase (two) to justify our assumption of a sine wave flux distribution over the pole face required for good generation. In the case of the pole piece laminations the only difference will lie in the length of the pole piece, which can be worked into the design prior to the manufacturing stage with a minimum of effort and expense.

The conductors shall be of annealed soft drawn copper, the electrical characteristics of which are given in the table next below. This is called copper of 100 percent conductivity and the figures are taken from the values given by the Bureau

of Standards in Circular No. 31 and adopted as standard by the A.I.E.E.

Characteristics of copper as a Conductor, 100% conductivity: temperature, Centigrade degrees – 0 – 25 – 75 – 100

	0	25	75	100
1. Resistance of 1000 ft. of 1 sq. m. section	0.0075	0.0083	0.0099	0.0107
2. Resistance of 1 ft. of 1 circ. mil section	9.55×10^{-6}	10.55×10	12.6×10	$13.63\times$
3. Relative resistance	1.00	1.108	1.32	1.427

It is customary to operate the copper conductors of electric machines at densities of current from 1000 amperes per square inch to 3000. On small or very well ventilated machines where the heat generated is of a low value, the higher value will be found. In our particular case it was found after some estimations and preliminary calculations that a value of some 1200 amperes per square inch was very satisfactory, and this value level was utilized throughout.

3. The dielectric circuit consists of the insulating material which separates the copper conductors from one another and from the steel core and frame of the machine. The function of this circuit is to make it possible to arrange conductors lying adjacent to one another in a series circuit so that the voltages induced in them will be additive in a predetermined manner. It also confines the current to a definite path in the wires instead of allowing it to stray through the frame of the machine.

The properties which a good insulating material should have are four in number, namely:

(1) A high resistance to the flow of current. This is known as insulation resistance.

(2) The ability to withstand a high voltage across a small thickness without breaking down and permitting current to flow. This is known as dielectric strength.

(3) A reasonable mechanical strength to withstand bending, vibration, abrasion, and shock.

(4) The ability to conduct the heat energy from the conductors to the body of the machine without an excessive difference in temperature.

The insulation resistance of a machine is measured from the copper of the winding through the insulation to the frame of the machine. Its magnitude depends greatly upon the presence of dirt and moisture, particularly moisture. Drying or baking will usually increase the insulation resistance greatly. Usual values for the proper insulation resistance of machines vary from 50,000 ohms to several million ohms. The higher values are for smaller machines and high-voltage machines. Standardization rules of the A.I.E.E. cover this matter with thoroughness.

The specifications of our machine require an insulation resistance of the stator and field windings when corrected to 25 degrees Centigrade, of not less than 25 megohms for our Class A insulation.

The dielectric resistance of an insulating material is measured by applying an alternating voltage to a sample of the material of a specified thickness, and gradually increasing the voltage until the insulation breaks down, a spark passes, and an appreciable current flows. The root mean square of the voltage which caused the break-down is specified as the

dielectric strength of the sample. A conventional figure of the dielectric strength of a material is often specified as the root mean square of that alternating voltage which a sample of a thickness of one mil will stand for one minute.

The mechanical strength of an insulating material is not capable of being defined specifically. One test is to determine how many times a thin sample will flex at right angles, first one way then the other, without breaking.

In reference to the effect that high temperatures will have on them, insulating materials are divided into classes. The Standardization Rules of the A.I.E.E. state that cotton, silk, paper, and similar materials impregnated with varnish, will not stand a higher temperature than 105°C. without becoming permanently damaged, while mica, asbestos, and similar materials can stand temperature up to 125°C. without becoming permanently damaged. It is an inherent characteristic of electric machines that their various parts become heated during operation because the various losses turn into heat. Consequently the limit to the output of such a machine is the maximum temperature which its most delicate part will stand without permanent injury. The insulation is most easily injured by heat, hence the necessity of knowing what temperature it can stand without damage and limiting the output of the machine to that value which will not produce a temperature so high that the insulation will be ruined.

The ability to conduct heat is desirable, since the copper windings of the machine are usually the hottest part

and the only way the heat can escape the copper is through the insulation. The better the heat-conducting qualities of the insulation the lower will be the difference in temperature between the copper and the surrounding air. It is unfortunate that all the materials that are insulators for electric currents are also very poor heat conductors, so that the designer has to do the best he can to get around this tendency of nature. Impregnating the cotton fabrics with oil or varnish and making them solid is one way of making them better conductors of heat. An alternate way, and the way we choose, is to reduce their thickness so that the temperature gradient is low from copper to surrounding air and in that manner let the air be the heat dissipating medium. The problem in this case, for our armature conductors, was to get an insulating varnish with a high dielectric strength that would withstand the copper temperatures. After calculating the copper temperatures, and the 'hot-spot' temperatures of each slot, we found that any insulating varnishes such as G-E's Numbers 9435, a synthetic resin asphaltic varnish, or 7148, their phenolic, modified Glyptal base varnish would do the job. These varnishes have a thin dried covering thickness, a high flash point, greater than 1500 volts per mil dielectric strength, excellent adhesion, toughness, hardness, flexibility, penetration, bonding, and ageing flexibility. Their resistance to usual chemicals is from good to excellent in rating, and they can be either air dryed or baked to the coils.

In the case of our field coils, the covering will be double cotton covered. Cotton is applied in the form of a spun braid to the wires before they are wound on the coils. The double cotton covering has a thickness which increases the overall diameter of the wire from 0.072 inches to 0.085 inches. The cotton is left dry and natural until the coil is made up, and then the whole coil is impregnated with varnish in order to exclude moisture and to give the coil insulation better heat conducting qualities. Cotton tape will be used to bind the finished coil for mechanical protection.

As we have already stated we used an enamel coating for the armature conductors. It is applied by running the preformed wires through a small vat containing the varnish. The coating is assumed to be very thin, about 0.002 inches. It is reputedly very brittle and therefore can only be used where there are no sharp bends. This becomes a design problem, but preliminary investigations indicate that in our case, the wire is of such a size and follows such a path that there are no bends whose radius is less than the widest section of the wire, and those bends that do exist are only half a quadrant in arc in these cases.

4. General limitations in design and choice of cardinal dimensions.

Preliminary dimensioning for the first calculations of any machine require that these three factors be taken into consideration. They are the three fundamental limiting factors. If reasonable values are assigned to these, a workable

design is easily deduced. The factors are:

(1) The peripheral speed at the periphery of the armature or revolving part, the pole shoe outer perimeters, usually expressed in feet per minute, is generally tabulated in the reference for our size machine as from 2,000 to 5,000 fpm. We used the formula, using k_3, (pole pitch/length arma. core), equal to unity for best utilization of available space, which appears as shown below on the design sheets used at the Naval Postgraduate School:

$$V = 124 \sqrt[3]{\frac{k_3 \ K_a \ R \ n}{\Delta \ B_g}}$$

This formula gives a peripheral velocity of some 2,840 fpm which lies well within the values generally accepted as satisfactory for a machine of our design size.

(2) The magnetic density in the air gap or at the pole face, which we choose from tabulated values given in the various references on the subject as 30,000 lines per square inch, is another of the three limiting factors. The value of this is limited by the amount of m.m.f. we can afford to put on the poles and the amount of core loss and consequent heating in the iron, as a high value of B in the gap infers also a high density in the armature.

(3) The third factor is the density of the current stream on the surfaces of the armature, what we term peripheral current density, Δ, expressed in ampere conductors per inch of periphery, that is, the product of the total number of conductors on the armature surface multiplied by the current in

each conductor and divided by the perimeter of the armature. It can be seen that this is a measure of the total loss in the copper of the armature of the machine and of the heat produced thereby.

5. Discussion of the arbitrary constants.

(1) Ratio of pole arc to pole pitch.

This factor is governed by two opposing phenomena. For the sake of a small magnetic leakage and good form factor of e.m.f. wave, a low value of this ratio is desired to reduce the pole-to-pole flux leakage. For the sake of low reluctance to the main flux and economy of material in the whole machine, a high ratio is desired. The usual range for rotating fields in the size machine we have is from 0.5 to 0.7, and we have chosen a conservative 0.65 which worked out satisfactorily. At the bases of adjacent poles the field windings of these adjacent poles come within one half inch of meeting, therefore providing sufficient space for passage of cooling air as well as utilizing as much of the available space as is deemed prudent for the cooling required.

(2) The pole face, or air gap density.

This flux density is limited by the exciting ampere-turns on the field required to produce the flux, the length of the air gap radially, and sometimes by the heating of the iron from the core losses. The range is from 30,000 to 60,000 lines per square inch of section. We chose 30,000 for our small machine of low speed in order to reduce the size of the machine and also to reduce the effect of the core loss heating.

(3) The peripheral current density, Δ , is limited by the copper loss it produces and distortion produced by the armature m.m.f. We feel that our machine with its one ventilating duct is exceptionally good for ventilating requirements, and also because our insulation is conservative, we can choose a fairly high value of Δ . Ours is in the neighborhood of 1200, some 300 units greater than recommended for a low-speed, solid stator type machine.

(4) The peripheral velocity.

This velocity is altogether a function of the mechanical design, which fortunately in our case reaches no great moment. Usual value for which there appears no great concern as to mechanical stress limiting values are from 2,000 to 6,000 f.p.m.

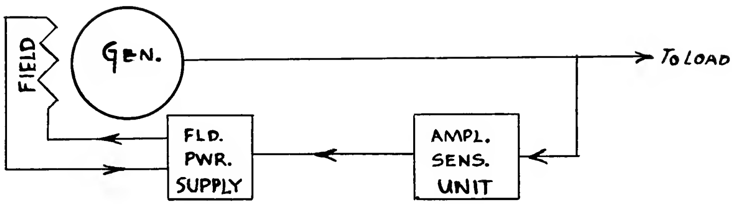
(5) The armature diameter is usually set when the speed is chosen, since ordinarily the speed in r.p.m. at which the machine is to run is one of the specified conditions. Combined with this dimension is the length, ℓ , of the armature between heads or end bells. It is dependent upon the ratio between the internal KVA of the machine and the product of the specific output and diameter chosen.

We now have discussed, in general terms, the magnetic circuitry, the insulation and windings problems, and some aspects of the ventilation and rotative speed problems. Now we shall turn to a discussion of the static voltage regulation and field excitation of our machine, its circuit, and how it is to operate.

VI - THE REGULATION AND FIELD EXCITATION

This particular chapter deals with that portion of the design which interested me in the idea of the design as a thesis subject. I admit now that to fully cover the complete subject would require more time than there is (and was) available. In order not to fail to include some discussion on the subject of this chapter, I am putting down on paper a system which I believe can be worked out for such a machine as I have designed. It will meet the letter of the specification which precludes use of electronic devices which if they fail will cause failure of the system.

This is the basic block diagram of the system of regulation and field supply.



This is a Ward-Leonard REACTROL voltage regulator system. The REACTROL voltage regulator changes the generator field excitation in reverse relation to the changes in the output voltage of the generator. Therefore it resists any change in the generator output voltage.

Field voltage of this system is produced as a function of load and power factor. It is in inverse relation to changes in generator voltage due to load changes.

The amplifier sensing unit contains three major circuits.

They are shown on the attached Figure 17, the circuit of the block diagram above.

The three circuits are: 1 - The constant voltage circuit; 2 - The variable voltage circuit; and 3 - The magnetic amplifier circuit. They will be identified in this discussion as circuits 1, 2, and 3. The outputs of circuits one and two oppose each other and their resultant is fed to the control winding of the first stage of the third circuit, the magnetic amplifiers. When circuits one and two outputs are equal, no current flows to three. When circuit two output current is less than that of number one, current flows in one direction, and when the opposite situation exists, the reverse occurs. The power level of this current is too low for direct operation of the saturable reactors L6, L7 and L8, in the field power supply, and therefore the magnetic amplifiers circuits are used to elevate this power supply to the reactors.

In circuit three the output of the anode windings is controlled by the control circuit windings and the anti-hunt windings. The control windings change the saturation of the field power supply saturable reactors in proportion to the current flowing in them, thus changing the impedance of the anode windings in reverse proportion so that the output of the anode windings changes in proportion to the control current from one and two. The current flowing through the anti-hunt windings modifies the response of the saturable reactors to damp the oscillations of the system and thus prevent hunting. The second stage of the third circuit is the same as the first. The inclusion of the second stage, because of the transient re-

sponse time shortening characteristic of magnetic amplifiers, is made to reduce the time of response of the field power supply to changes in the generator output.

Whenever the generator voltage causes this difference between the constant and variable voltages to increase in a positive direction due to changes in the machine load, temperature, or RPM, the magnetic amplifier output goes up and increases the saturation of the field power supply reactors L6, L7 and L8. This in turn causes more power to the field, and the generator output is increased. This last increase causes a reduction in the difference of circuits one and two.

Rectification is accomplished at various points along the path of the difference of circuit one and two outputs, and arrives at the field in the sense indicated.

Power for the field up to no load conditions of generator output is supplied by the starting batteries of the diesel driver.

APPENDIX

1. The Calculations.

The calculations which follow are based upon the assumptions that the calculator has basic knowledge of alternating current theory and the use of vectors. The treatment will be kept as free of unreasonable assumptions which in the design of any machine will make it impossible. On the other hand, the only assumptions which will be made will be those which are consistent with design practices of the major concerns doing this type of work today. The form followed will be that used by the students of the Naval Postgraduate School as compiled by Professor C. V. O. Terwilliger, Head of the Department of Electrical Engineering at that institution.

We shall assume that the designer has the basic knowledge connected with elementary electric circuits, the variation of resistance with temperature, open coil wire resistances, insulated coil wire sizes, capacities, insulation thicknesses, dielectric circuitry, insulation permittivities of various types and thicknesses of insulation to be encountered in this size machine.

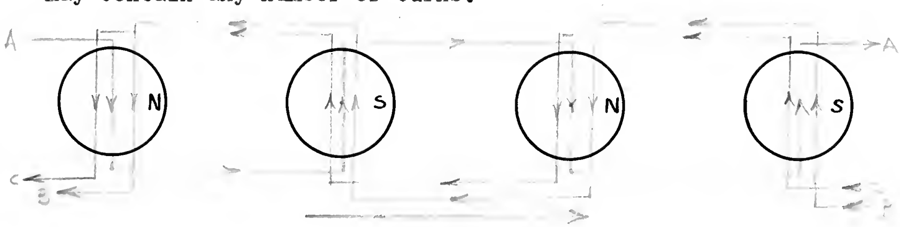
The number of poles of the alternating current generator depends directly upon the speed in revolutions per minute of the machine and the designed frequency of its output. Our RPM and frequency are 360 and 60 respectively, as stated in the specifications for the machine.

Our machine will have salient poles because of their lessor cost than the machined rotor case, and also because we

need not worry about the peripheral speed of the field pole tips since they are going to rotate at but 360 R.P.M. at a diameter which we know from previous observation to be less than say, three feet in diameter. The stresses set up in the pole roots will be of such a small magnitude that there will be no major problem at this point. As it turns out there will be a peripheral speed of the field pole pieces at their extremities of but some 2800 f.p.m. and the mechanical stresses set up at the tooth roots, as shown in later calculations, will be of the order of twelve hundred pounds per square inch of root area, insufficient to cause concern.

The number of phases is set by the specifications to be three. This will not affect the design as far as its complexity is concerned, and so we shall spend no time discussing the aspects which should be noted in this instance.

Whatever may be the type of machine we shall end up with, we may consider the armature conductors to be cut by the magnetic lines in the manner indicated in the figure below. The alternate pole pieces are supposed to move across the armature conductors in the direction indicated by the green arrow. The conductors are connected in a simple wave winding only to simplify the diagram, and it is readily understood that each coil may contain any number of turns.



Attention is paid to the manner of each coil's connections to the succeeding coil, in order that the e.m.f.s generated in the various coils shall not oppose each other. It should also be noted that these coils indicate a full pitch winding whereas our winding will be a 5/6ths pitch in order to cut down on the 5th and 7th harmonics arising in the generation of the e.m.f. in each coil. There are no 3rd, 9th, 15th, and further odd harmonics to worry about in the two conductor per coil, 5/6ths pitch, star connected, lap winding which we have chosen for our machine. The figure shows the coil A position when its generated e.m.f. will be a maximum, while in B coil it is 120 degrees from the A coil, as is the case of the C coil also. The e.m.f. in the A coil is at a maximum, then, while in coils B and C the e.m.f.s are of a smaller value and in opposite directions.

Usual speeds of alternating current generators are listed in this table following:

Output, KW	No. of poles	Speed, RPM
0 to 10	2 or 4	2,400 to 600
10 to 50	4	1,300 to 350
50 to 100	4 or 6	1,100 to 250
100 to 300	6 or 8	800 to 200
etc.		

Our machine falls in the 50 to 100 KW output class, and our r.p.m. fall into line, being 360 by the specifications.

We shall assume without compunction as to its veracity in our design, that the form factor for distributed windings

shall be 1.11. The development of this value is based upon the assumption that the space distribution of the flux density over the pole pitch follows the sine law, and if this is so, then the virtual value of the e.m.f. is 1.11 times the mean value. In other words, the <u>form factor</u>, or ratio of r.m.s. to mean value of the e.m.f., is $\pi/2\sqrt{2}$, or 1.11, in the case of the sine wave. As each coil side may be thought of as occupying a very small width on the armature periphery and if the coil sides of each phase winding are spaced exactly one pole pitch apart, the arrangement would consist of what is usually referred to as a concentrated winding. In practice a winding with only one slot per pole per phase would be thought of as a concentrated winding. When there are more than two or more slots per hole per phase, the winding is said to be distributed. One slot per pole per phase winding will not give true sine wave flux distribution necessary for our form factor assumption, and two slots per pole per phase is the minimum for this assumption within the limits of the accuracy required for a reasonable design.

We shall proceed now with the general calculations required to lay down the design of a generator such as required by our specifications. At this point it is well to note that there are several set methods to follow in any design of alternating current machinery. They all accomplish what the planner requires to assemble a workable machine. We refer to the text references of the bibliography for additional assumptions.

Procedure and Calculations:

1. Specifications.

Capacity - KW	KW = 75.00
Power factor -	PF = 0.80
Capacity - KVA	KVA = 93.75
No. of phase - p′	p′ = 3
RPM - R	R = 360
Terminal volts, full load -	E_ℓ = 240
Amperes, line, full load -	I_ℓ = 225.50
Regulation at PF -	0.80, = 3.0%
Frequency - n	n = 60 cps

RP 271

DEPARTMENT OF ELECTRICAL ENGINEERING

ALTERNATOR DESIGN—

Name C. F. SCHARFENSTEIN, JR. Date of beginning 1/3/50

Date of completion 1/17/50

SPECIFICATIONS

Capacity, $K.W. =$ 75.00

Power factor, $p.f. =$ 0.8

Capacity, $K.V.A. = K =$ 93.75

Number of phases, $p' =$ 3

If direct-coupled, $r.p.m. = R =$ 360

Frequency, $n =$ 60

Terminal volts, full load, $E_t =$ 240.0

Amperes line, full load, I_l

Inherent Regulation (non-inductive load) =

Regulation at power factor of 0.8 = ± 3%

Max. allowable temp. rise, degrees cent., $T =$ 50°C.

Other heating specifications —

PRELIMINARY APPROXIMATIONS

Type

Form factor, $k_f =$ 1.11

Ratio pole arc to pole pitch, $k =$ 1:1 for stator .65:1 for rotor

Peripheral current density, $\Delta =$ 1200

Resistance drop in armature $\div E$, $q_r =$ 0.018

Differential factor, $k_d =$ .966 $k_f k_d = k_{fd} =$ 1.07226

Mean gap density at pole face, $B_g =$ 30,000

Coil pitch ÷ pole pitch, g_p = 0.833

E.m.f. pitch factor, $k_p = \sin \frac{\pi}{2} g_p$ = 0.966

Leakage reactance drop $\div E$, $q_x = \frac{I_a X_a}{E_a}$ = 0.01

Internal volts $\div E = \sqrt{(q_r + p.f.)^2 + (q_x + \sqrt{1 - p.f.^2})^2} = q_{E_a} =$ 1.0206

Internal $K.V.A. = q_{E_a}K = K_a =$ 95.68

Star ~~or Delta~~ $\ast$

Terminal volts per phase, $E =$ 138.575

Internal volts per phase $q_{E_a}E = E_a =$ 142.5

Amperes per phase $= 1000 K_a \div (p'E) = I_a =$ 225.5

Number of poles = $2 \times 60 \times 60 \div 360$	$2p$	20							
$R.p.m. = 60n \div p =$ $\frac{60 \times 60}{10}$	R	360							
Peripheral velocity, ft. per sec. = see below	v	47.343 (1)							
Diam. of arm. at air gap $= 720v \div (\pi \times r.p.m.) =$	d	30.15	=	720 × 47.343 ÷ π × 360					
Specific output $= 12\pi k_p k_{fd} k v \Delta B_g 10^{-11} =$	k_0	0.6766	= 12π × 0.966 × 1.07226 × 47.343 × 1200 × 30000 × 10^{-11}						
Length arm. core $= K_a \div (k_0 d) =$	l	4.698	= 95.68 ÷ .6766 × 30.15						
Pole pitch $= 6v \div n =$	λ_p	4.73	=	6 × 47.343 ÷ 60					
Pole arc $= k\lambda_p =$	l_p	4.73	=	1 × 4.73					

If $k_3 \left(= l_p \div l\right)$ be assumed $v = 15 \sqrt[3]{\frac{k_3 K_a R_m}{\Delta B_g}}$

k_3 = 1 for a value of the constant of 124

(1) $v = 124 \sqrt[3]{\frac{1 \times 95.68 \times 360 \times 60}{1200 \times 30,000}} = 124 \sqrt[3]{0.054667} = 124(.3818)$

$= 47.343$ fps

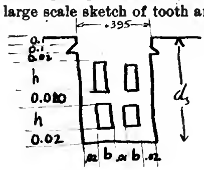
$= 2840$ fpm

Approximate Values		
Volts per inch of active conductor $= 12 k_{fd} k v B_g 10^{-8} =$ (k_p written above k_{fd})	e''	$0.1765 = 12 \times 0.966 \times 1.07226 \times 1 \times 47.343 \times 30000 \times 10^{-8}$
Total active conductor, inches, $= p' E_a \div e'' =$	l_{ac}''	$2355 = 3 \times 138.575 \div 0.1765$
Approx. total number of active cond's. $= l_{ac}'' \div l =$	N_a	$502 = 2355 \div 4.698$
Slots per pole per phase *assumed*		2
Total number of slots	N_t	120
Conductors per slot $= N_a \div N_t$	N_{cs}	4.18
Adjusted Values *Use* $N_{cs} =$		4
Total number active conductors $= N_{cs} N_t =$	N_a	$480 = 4 \times 120$
Active conductors per phase $= N_a \div p' =$	N	$160 = 480 \div 3$
Periph. current density $= N_a I_a \div \pi d =$	Δ	$1183 = 480 \times 225.5 \div \pi \times 30.15$
Allowable watts per sq. inch arm. copper $= \Delta \div \odot_a = (.5 \text{ to } 1.2) =$	h_c	$1.183 = 1183 \div 1000$
Min. Cir. mils per ampere in arm. copper $= \Delta \div h_c =$	$\odot_a$	1000 *assumed*
Section arm. cond. in cir. mils $= I_a \odot_a =$	$c.m._a$	$225500 = 225.5 \times 1000$
Section arm. cond. in sq. in's. $=$		$0.177 = \frac{\pi}{4} \times 10^{-6} \times 225500$
Flux (megalines) entering arm. per pole at full load $= 100 E_a \div (2 k_{fd} h N) =$ (k_p written above k_{fd}; 10^6)	$0.716541 = \Phi_f =$	$0.716541 = 100 \times 142.5 \div 2 \times 1.07226 \times 0.966 \times 60 \times 160$
Mean gap density at pole face $= \Phi_f \div l_p l =$	B_g	$32245 = 716541 \div 4.698 \times 4.73$
Volts per inch of active conductor - - - - - -	e''	~~0.18972 = 12 × 0.966 × 1.07226 × 1 × 47.343~~ $\times 32245 \times 10^{-8}$
Number of vent. ducts in arm. core *on basis of one for each 2 1/2" of armature length.*	N_d	1
Width of each duct – *assumed*	w_d	0."5
Net iron length of core $= .9 (l - N_d w_d) =$	l_i	$3.78 = 0.9 (4.7 - 1 \times .5)$
% net iron length $= l_i \div l$	k_i	$0.805 = 3.78 \div 4.698$
Tooth pitch $= \pi d \div N_t =$	λ_t	$0.79 = \pi \times 30.15 \div 120$
Desirable app. density at tooth tips *or neck* (rev. field assumed)	B_{tt}	$80116 = \frac{B_g \times 2}{k_i} = 32245 \times 2 \div 0.805$
Width tooth tip *or neck* $\div$ tooth pitch $= B_g \div k_i B_{tt}$	k_{tt} / g_{tt}	0.5 *assumed for best construction*
Width of tooth at tip $= g_{tt} \lambda_t =$	w_{tt}	$0.395 = \frac{1}{2} \times 0.79$
Width of tooth $\frac{1}{3} d$ from narrow end	w_{t3}	$0.42^{\pm}$ FIG. 6
Ratio of w_{t3} to $\lambda_t =$	k_{t3}	$0.532 = 0.42 \div 0.79$
Width of slot $=$	w_s	0.395
Depth of slot $=$	d_s	2.162
Gauge number. diam. or dimensions of arm. cond.	(1)	0.185 × 0.956 } about No. 0000 AWG
Thickness of slot insulation, iron to copper —		0.020 = Pressboard + enamel
Space factor of slot	f_{ss}	$0.72 = 4 \times 0.177 \div \left[.395 \times 2.162 + \frac{2.162 \times .065}{2}\right]$

Draw a winding diagram showing clearly the type of winding and the connections. See Figs. 1 and 15

Make a large scale sketch of tooth and slot showing conductors and insulation. See Fig. 6

(1)



$W_s = 0.02 + 0.01 + 0.02 + 2b$

$b = 0.''185$

$h = 0.177 \div b = 0.''956$

$d_s = 0.02 + 2h + 0.01 + 0.02 + 0.1 + 0.1$

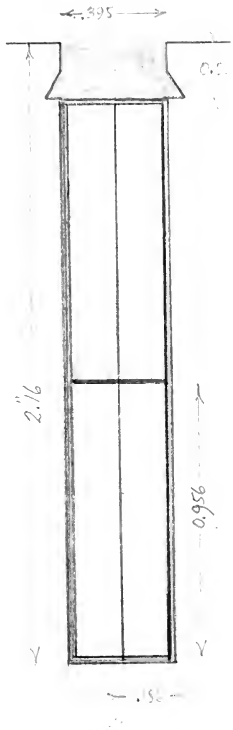
$= 2.''162$

[illegible]

[illegible]

Slot Section

Scale: 2"-1"



Index to colors
Black - wire enamel
Blue - 0.015" Press-board - GE Co.
Green - Copper Conductor
Red - Retaining wedge

NB: All dimensions are in inches;

FIG. 6

A

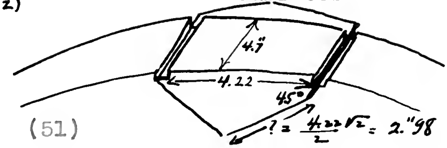
Armature Core			
Thickness of laminations, inches	t	0.014	1% Silicon Sheet Steel
Armature core density, assumed	B_a	23700	= 716541 ÷ 2 × 3.78 × 4.00
Section back of slots $\Phi_f \div 2B_a$	s_a	15.12	= 3.78 × 4.00
Radial depth back of slots $= s_a \div l_i =$		4.00	See above
Outside diam. arm. core	D_a	42.5	= 30.15 + 2 × 2.162 + 2 × 4.00
Volume core, excluding teeth, (cu. inches)	V_c	1830	$= 3.78 \times \frac{\pi}{4}\left[(42.5)^2 - (34.5)^2\right]$
Hysteresis watts per cu. inch $= 2\frac{n}{100}\left(\frac{B_{max}}{10^5}\right)^{1.6} =$	P_h'	0.12	$= 2 \times \frac{60}{100} \times (0.23)^{1.6}$
Eddy watts per cu. inch. $= \left(\frac{n}{100} \times \frac{B_{max}}{10^5} \times 100t\right)^2 =$	P_e'	0.0396	$= (.6 \times .237 \times 1.4)^2$
Total watts per cu. inch. $= P_h' + P_e' =$	P_{h+e}'	0.1596	
Total watts lost in core, excluding teeth =	P_c	293	= 1830 × 0.1596
Teeth			
Apparent density $\frac{1}{3}$ from narrow end $= B_g \div k_i k_{t3} =$	B_{ta}	75290	= 32245 ÷ 0.805 × 0.532
Corrected density	B_{tc}	118200	$= 32245 \times \frac{\pi}{2} \times \frac{4.698}{3.78} \times \frac{0.79}{0.42}$
Hysteresis watts per cu. inch		1.570	$= 2 \times .6 \times (1.18)^{1.6}$
Eddy watts per cu. inch		0.985	$= (.6 \times 1.18 \times .014 \times 10^2)^2$
Total watts per cu. inch		2.555	
Volume of teeth, cu. inches	V_t	416.5	$= \frac{1}{2} \times 3.78 \times \frac{\pi}{4} \times (34.50^2 - 30.15^2)$
Total watts lost in teeth	P_t	1065	= 416.5 × 2.555
Total Iron			
Load loss due to distortion, [25% of $(P_c + P_t)$] =	P_l	338	$= \frac{1}{4} \times (293 + 1065)$
Total iron loss $= P_c + P_t + P_l =$	P_i	1696	= 293 + 1065 + 338
Iron loss in terms of output = 1696 ÷ 75000	q_i	0.0225	(P 297 Still)
Copper			
Actual section arm. cond. in cir. mils	$c.m._a$	225500	
Corresponding cir. mils per ampere $c.m._a \div I_a =$	$\odot_a$	1000	= 225500 ÷ 225.5
Active length arm. cond. ÷ gross length =	k_4	0.421	See (2) below
Length arm. cond. inches per phase $= Nl \div k_4 =$	l_{ac}'	1783	= 160 × 4.7 ÷ 0.421
Hot resistance per phase $= l_{ac}' \div c.m._a$	r_a	0.0079	= 1783 ÷ 225500
% resistance drop $= I_a r_a \div E_a = 1 \div (k_4 e'' \odot_a) =$	q_{ac}	0.0125	= 225.5 × 0.0079 ÷ 142.5
Total arm. copper loss $= p' I_a^2 r_a =$	P_{ac}	1205	$= 3 \times \overline{225.5}^2 \times 0.0079$
Total armature loss $= P_i + P_{ac} =$	P_{at}	2901	1696 | 1205

Total Cu. Vent.
Surfaces

$\left\{ \begin{array}{l} 3.78 = l_i \\ 4.00 = \text{assumed core depth} \\ \text{See (1) below} \end{array} \right.$

(1) Page 370 "Still"
Net radial depth below slots =
$= \Phi_f \div 2\, B_a\, l_i$
$= 716541 \div 2 \times 23700 \times 3.78$
$= 3.94$ ins.

(2)



Armature Heating

		Total	Cu Surf.	Vent. Surf.	
Peripheral surface or arm. including coil ends	S_a	3740	2310	1430	(1)
Watts dissipated per sq. in. per deg. cent.	H_a		$0.012^{\pm}$	0.025	Page 235—WALKER
Temperature rise of arm. $= P_{at} \div H_a S_a = \frac{1205}{.012 \times 2310}$ and $\frac{1696}{.025 \times 1430}$	T_a		43.5°	47.4°	

If this exceeds the allowable temp. rise a readjustment must be made.

Magnetic Circuit

	a Arm. Core	*t* Teeth	*m* Mag. Core	*y* Yoke	air gap
Leakage coefficient at full load	—	—	1.18	—	—
Flux at full load	716 541	188 000	171 000	—	—
Material	STEEL	STEEL	$\frac{1}{16}$" POLE IRON	FORGED STEEL	AIR
Density, full load	23 700	118 200	38 000	75 000	32245
Net section, sq. inches	15.12	1.59	4.5	4.56	21.25
Mag. length for a complete mag. circuit Fig. 7	4.6	2.16	4.28	2.12	0.25

Make scale drawings (two sections) of magnetic circuit. SEE FIG. 7

Compute and plot a magnetization curve (E_a vs. Ni) for each of the above parts of the magnetic circuit, and one for all of them together. SEE FIG. 8

Arm. flux per pole % of Φ_f	Φ $\times 10^3$	B_a $\times 10^3$	Ni_a	B_{tc} $\times 10^3$	Ni_t	Φ_m $\times 10^3$	B_m $\times 10^3$	Ni_m	B_y $\times 10^3$	Ni_y	Total for Iron Ni_i	E_a	B_g $\times 10^3$	Ni_g
.70	502	16.6	7	82.8	21		26.6	42.8	52.5	46	117	99.7	22.6	1770
.80	564	19.0	8	94.6	56		30.4	43.0	60.0	57	164	114.0	25.8	2020
.90	645	21.3	8	106.5	135		34.2	45.0	67.5	70	248	128.2	29.0	2276
.95	681	22.5	8	112.5	431		37.1	47.0	71.3	78	465	135.3	30.6	2400
1.00	716.5	23.7	8	118.2	647	171	38.0	49.0	75.0	85	790	142.5	32.2	2540
1.05	753	24.9	9	124.2	1015		39.9	50.0	78.8	93	1267	149.7	33.9	2660
1.10	788	26.1	9	130.0	1562		41.8	52.0	82.5	103	1726	157.0	35.4	2770
1.20	860	28.4	9	142.0	3451		45.6	56.0	90.0	130	3647	171.2	38.7	3130
1.30	930	30.8	10	154.0	6340		49.4	65.0	97.5	186	6600	185.4	41.9	3290

$$NI_{\text{air gap}} = 0.313 \times l_{\text{air gap}} \times B_g$$

(1) External Conductor Surface area $= \left[(4.7-.5)+4.22\right]\pi \times 30.15 + 2 \times \frac{\pi}{4}\left[(30.15+2\times2.162+2\times4)^2-(30.15)^2\right]$

$= 2310 \text{ in}^2$

Ventilating duct surface area $= 2 \times \frac{\pi}{4}\left[42.5^2 - 30.15^2\right]$

$= 1430 \text{ in}^2$

Machine Section - not to scale
Dimensions in inches

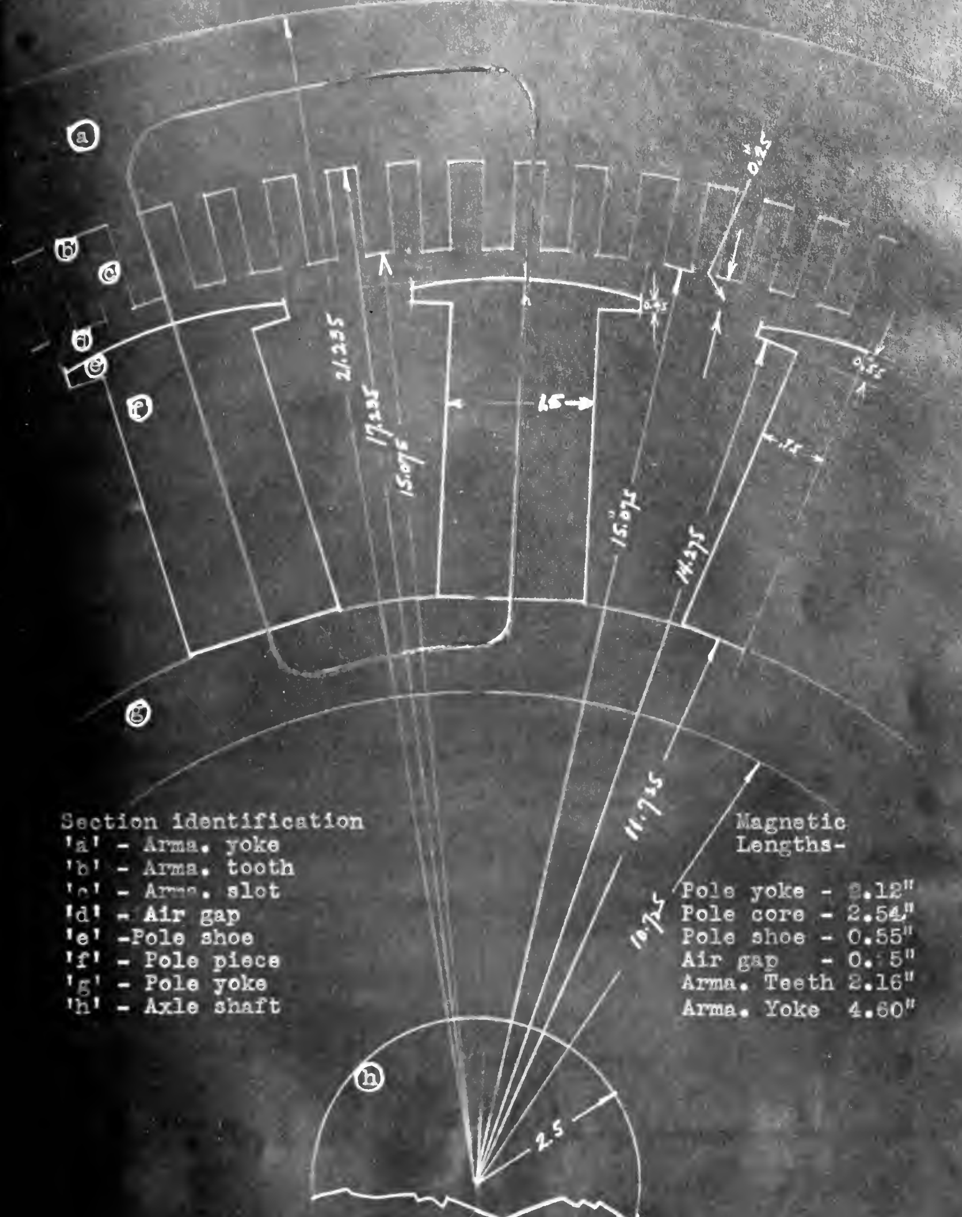


FIG. 7

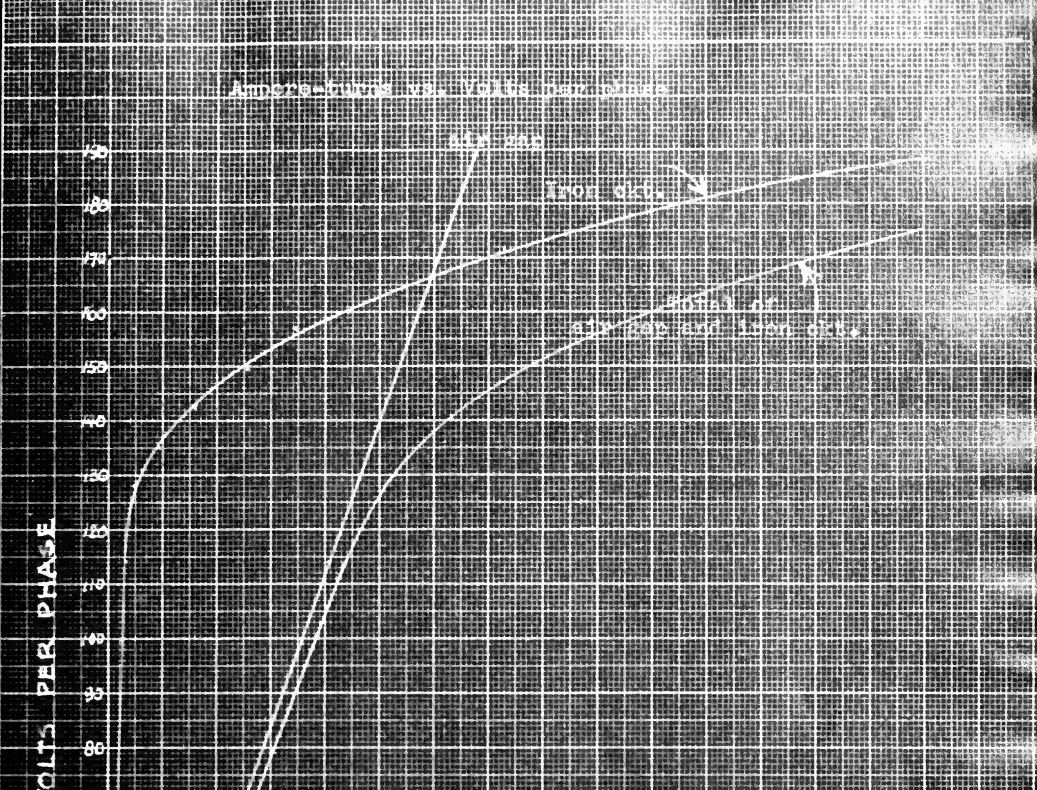

Ampere-turns vs. Volts per phase
air gap
Iron ckt.
Total of
air gap and iron ckt.
VOLTS PER PHASE
0
1000
2000
3000
4000
5000
6000
7000
Ampere Turns

FIG. 8

Armature vector amp. turns for a complete mag. circuit $= .71\,\Delta\,\lambda_p =$	A	3840	= 0.71 × 1183 × 4.73		
Approx. total equiv. arm. amp. turns including effect of leakage drop $= k'A =$	A'	4608	= 1.2 × 3840		
Where $k' =$	k'	1.2	20%	leakage drop assumed	
Approx. percent drop due to equiv. arm. res. $\doteq I_a r_e \div E = 1.5 q_{ac} =$	q_{re}	0.01875	= 1.5 × 0.0125		
Approx. saturation factor at full load =	f_s				
Desired regulation =	q				
$F \div R' = f_s\,(q - q_{re}) + 1 =$	a				
Approx. full load field ampere turns $= a A' \div \sqrt{a^2 - 1} =$	F				
Reluctance ampere turns $= R'\sqrt{1 + q_x^2} = \frac{F}{a}\sqrt{1 + q_x^2} =$	R				
Amp. turns in iron at full load, (from saturation curve) =	Ni_i	790			
Amp. turns in single air gap at full load $= (R - Ni_i) \div 2 =$	Ni_g	2540			
Assume air gap contraction coefficient for slots and ducts = .75 to 1.0		1.00			
Approx. air gap for calculation of fringing $= 0.75\,Ni_g \div 0.313\,B_g =$		0.25	= 2540 ÷ 0.313 × 32245		
Tooth fringing constant* $= 0.6 + 1.47 \log_{10} \frac{w_s}{2\delta} =$	f_t	0.75	= 0.6 + 1.47 $\log_{10}$ .5/.5		
Effective pole arc $= (l_p + 2\delta)\,(w_{tt} + 2\delta f_t) \div \lambda_t =$	l_{pe}	4.03	= (4.73 + 0.5)(0.395 + .5 × 0.625) ÷ 0.79		
Duct fringing constant* $= 0.6 + 1.47 \log_{10} \frac{w_d}{2\delta} =$	f_d	0.60	= 0.6 + 1.47 $\log_{10} \frac{.5}{.376}$		
Effective length of arm. core $= l + \delta - N_d\,(w_d - 2\delta f_d) =$	l_e	5.3	= 4.7 + .25 − 1(.5 − .5 × .7825)		
Effective gap section $= l_e l_{pe} =$	s_{ge}	21.37			
Corresponding gap density at full load =	B_{ge}	33500			
Min. safe air gap $= Ni_g \div 0.313\,B_{ge} =$	δ	0.242	= 2540 ÷ 0.313 × 33500		

Draw air gap line on same sheet with total iron magnetization curve, and add the two to get the total saturation curve. See Fig. 8

* For values of $\frac{w}{2\delta} < 1$, $\quad f = \left(1 - 0.4\,\frac{w}{2\delta}\right)\frac{w}{2\delta}$.

A

Slot Leakage

Flux per ampere inch of slot $= 3.2\left(\frac{1}{3}\frac{d_1}{W_S}+\frac{d_2}{W_S}+\frac{2d_3}{W_3+W_4}+\frac{d_4}{W_4}\right)+1.1 =$	ϕ_s'				
Slot width divided by tooth pitch $=$	b_s''				
Slot constant $= \lambda_t\phi_s' = \frac{d_s}{b_s''}$ * (1.2 to 3.)*	k_s				
Slot pitch factor, k_{ps}	k_{ps}				
Slot leakage volts in terms of $E_a = 2\pi k_s k_{ps} n \Delta 10^{-8} \div e'' =$	q_{xs}				
Tooth-Tip Leakage $q_{xs} = .68\, k_s \frac{k_{ps}\, n\, \Delta}{k_p\, v\, B_g}$					
Flux per ampere inch of slot	ϕ_{tt}'		See pp.	66	
Slots per pole	N_{sp}				
Tooth-tip constant $= 4.4\,\phi_{tt}' \div N_{sp} =$ (1.2 to 2.5)	k_{tt}				
" " pitch factor, k_{pt}	k_{pt}				
Tooth-tip leakage volts in terms of $E_a = k_{tt}\frac{\Delta k_{pt}}{B_g k_p} = 8.6 k_{tt}\frac{\Delta v k_{pt}}{10^8 e''} =$	q_{xt}				
Coil End Leakage					
Flux per ampere inch of end belt	ϕ_f'				
Ratio free length to active length $= \frac{1}{k_4} - 1 =$	k_{fa}				
Coil end pitch factor k_{pc}	k_{pc}				
Coil-end leakage volts in terms of $E_a = 12.6\,\phi_f' k_{fa} k_{pc} \Delta v 10^{-8} \div e'' =$	q_{xf}				
Total percent Leakage Volts $= q_{xs} + q_{xt} + q_{xf} =$	q_x	0.0166 =	1.66%		

REGULATION AND EXCITATION

Non-Inductive Load

Total induced volts $= E\sqrt{(1+q_{re})^2 + q_x^2} =$	E_a	140.5			
Corresponding ampere turns from saturation curve — For complete magnetic circuit	R	3125			
Arm. vector ampere turns at full KVA. load	A	2275	(1)		
Total field ampere turns for noninductive load	F_n	3850			
Corresponding no load volts	E_F	151.5			
Regulation $= (E_F - E) \div E =$	q	9.3			

If this differs much from the specified regulation the air gap or the saturation must be altered and calculations repeated.

Inductive Load of power factor $=$

(1) $A = \sqrt{2} \times 3 \times \frac{1}{2} \times \frac{4}{\pi} \times k_p \times k_b \times S \times N \times I_{RMS}$

$= \sqrt{2} \times 1.5 \times \frac{4}{\pi} \times .966 \times .966 \times 2 \times 2 \times 225.5$

$= 2275$ NI

	E_a	142.5			
	R	3200			
	A	2275	(1)		
	F_t	4825			
	E_F	160.0			
	q	15.45			

Draw vector diagram to scale for each of these cases and plot an excitation characteristic for each. See Fig. 9

* Low values for open slots and high values for nearly closed slots.

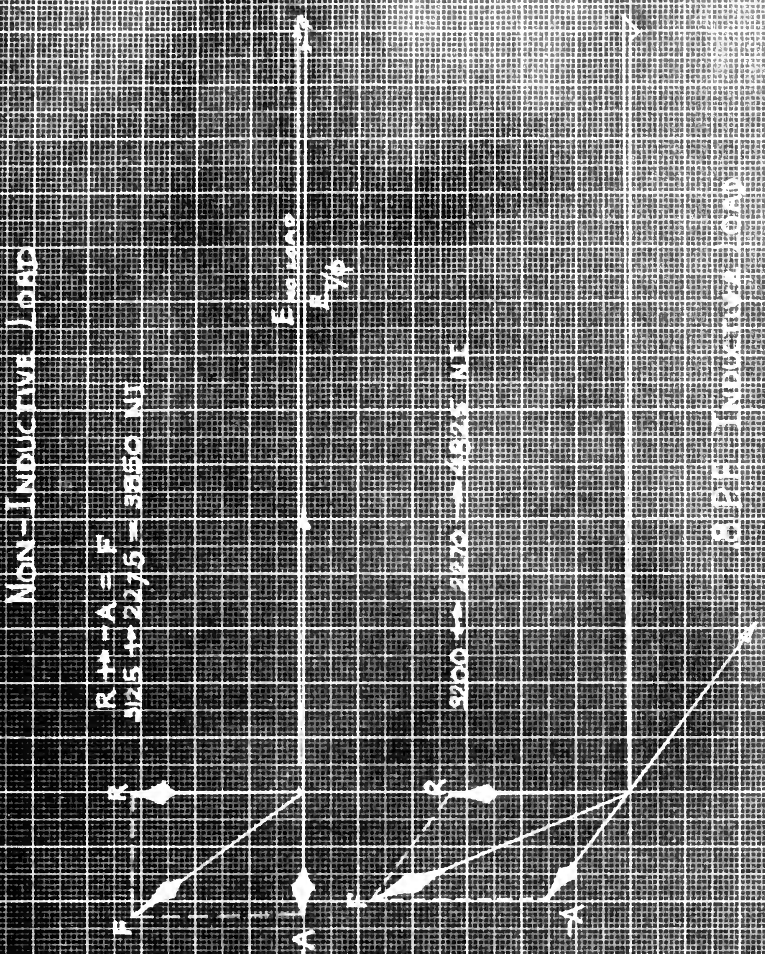

NON-INDUCTIVE LOAD
R + -A = F
3125 + 2275 = 3850 NI
E NO LOAD
E 1/φ
3200 + 2270 = 4825 NI
.8 P.F. INDUCTIVE LOAD
F
R
-A

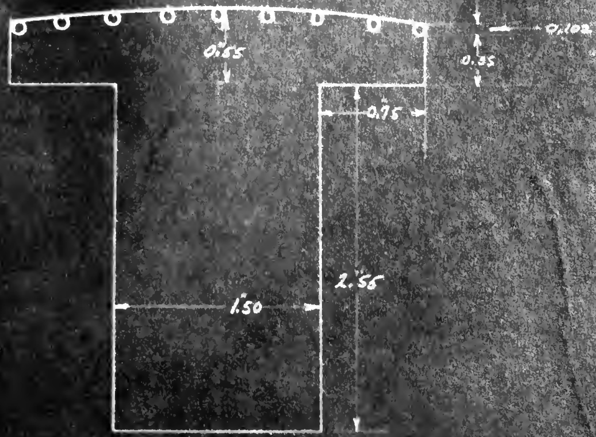
FIG. 9

Exciting *e.m.f.* Field supply circuit must be designed to give =	E_s =	120			
Volts allowed for field rheostat = 10% to 15% of E_s = assume 16.7%	E_r	20			
Volts per coil = $(E_s - E_r) \div 2p$ =	E_s'	5	= (120	-20) ÷	20
Depth of winding space = assumed	D_s	0.75±			
Mean length of one turn in inches assuming k = 0.65 and pole section = 3 x 1.5	l_s''	11.36			
Section in cir. mils = $(Ni_s = F_t \div 2)\ l_s'' \div E_s' = c.m._s$		5500	$= \frac{4825}{2} \times 11.36 \div 5$		
Dimensions of wire or conductor:		0.084	O.D.,	D.C.C.	No. 13 AWG
Watts per square inch of total coil surface per deg. cent. =	H_f	0.0135	P. 302	STILL	
Allowable temp. rise of coil surface =	T_f	50-60			
Cir. mils per amp. in field coil = $500\sqrt{D_s \div H_f T_f}$ =	$\odot_s$	527	$= 500\sqrt{0.75 \div 0.0135 \times 50}$ (or 60)		
Amperes field = $c.m._s \div \odot_s$ =	I_s	10.5 MAX 9.8 MIN			
Turns per spool = $Ni_s \div I_s$ =	N_s	246 MAX 230 MIN			
Arrangement of conductors, sketch. See Fig 10		8x30			

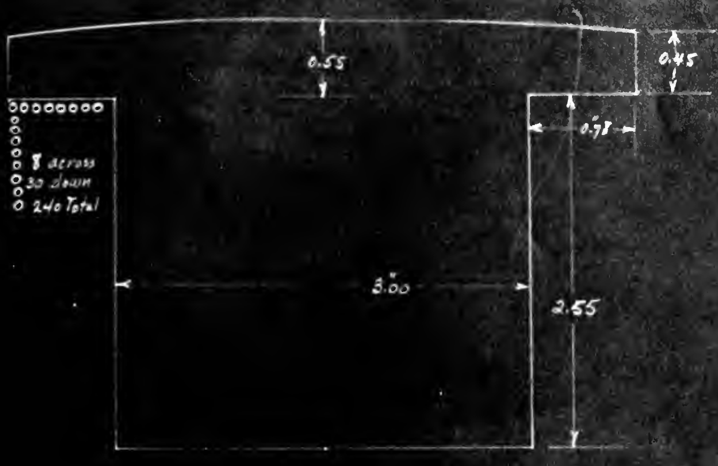
THERMAL CALCULATIONS

Armature					
Total iron loss	P_i	1700			
Copper loss at 60° cent.	P_{ac}	1200			
Total loss	P_a	2900			
Peripheral radiating surface including coil ends	S_a	3750			
Watts per sq. in. of radiating surface $= P_a \div S_a$ =	P_a''	0.755			
Watts radiated per sq. in. per deg. cent. =	H_a	0.018	average		
Temperature rise in deg's. cent. $= P_a'' \div H_a$ =	T_a	43°C			
Field Spool					
Copper loss per spool	P_s'	55±	= 10.5 amps x 5 volts		
Total coil surface per spool	S_s'	76 in²	= outer + inner + ends		
Watts per sq. in. of surface $P_s' \div S_s'$	P_s''	0.725			
Watts radiated per sq. in. per deg. cent.	H_f	0.0135	P.303	STILL	
Temperature rise in deg's. cent $= P_s'' \div H_f$ =	T_f	53°C	$= \frac{0.725}{0.0135}$		

Field Pole
Sections



End View



Side View

Fig. 10

Load in percent of full load		25	50	75	100	125
Armature current per phase	I_a	56.4	112.75	169.15	225.50	281.90
Output (watts)	P_o	18750	37500	56250	75000	93750
Fixed Losses = Core + Friction + Field Copper =	P_F	←		4300		→
Armature Copper Loss	P_{ac}	80	320	715	1275	1990
Input = $P_o + P_F + P_{ac}$	P_I	23130	42120	61265	80575	100040
Efficiency = $P_o \div P_I$ =	%	81.00	89.00	91.80	93.00	93.75

Plot Efficiency Curve. See Fig. 11

WEIGHTS AND COSTS

	Weight Lbs.	Cost, Dollars		Weight Lbs.	Cost, Dollars	
		Per lb.	Total		Per lb.	Total
Copper						
Armature $3 \times \frac{1785}{3} \times \frac{653 \text{ lbs}}{1000 \text{ ft}} = 285 \pm$	300					
Field $20 \times 357.6 \times \frac{15.7 \text{ lbs}}{1000 \text{ ft}} = 120 \pm$	150					
Total	450					
Per K. W.	0.167					
Magnetic Iron						
Arm. Laminations $\frac{0.28 \text{ lbs}}{\text{in}^3} \times (1830 + 211) = 600$	650					
Magnet Cores } $0.28 \times 20 \times 14.74 = 96$	75					
Pole Faces }	35					
Yoke $0.28 \times \pi 18 \times 4.7 \times 1.0 = 100$	100					
Total	860					
Per K. W.	0.0875					
Total Active Material						
Total	1310					
Per K. W.	0.0573					

Phase terminal volts; Efficiency; Load amperes -
versus Percent Load

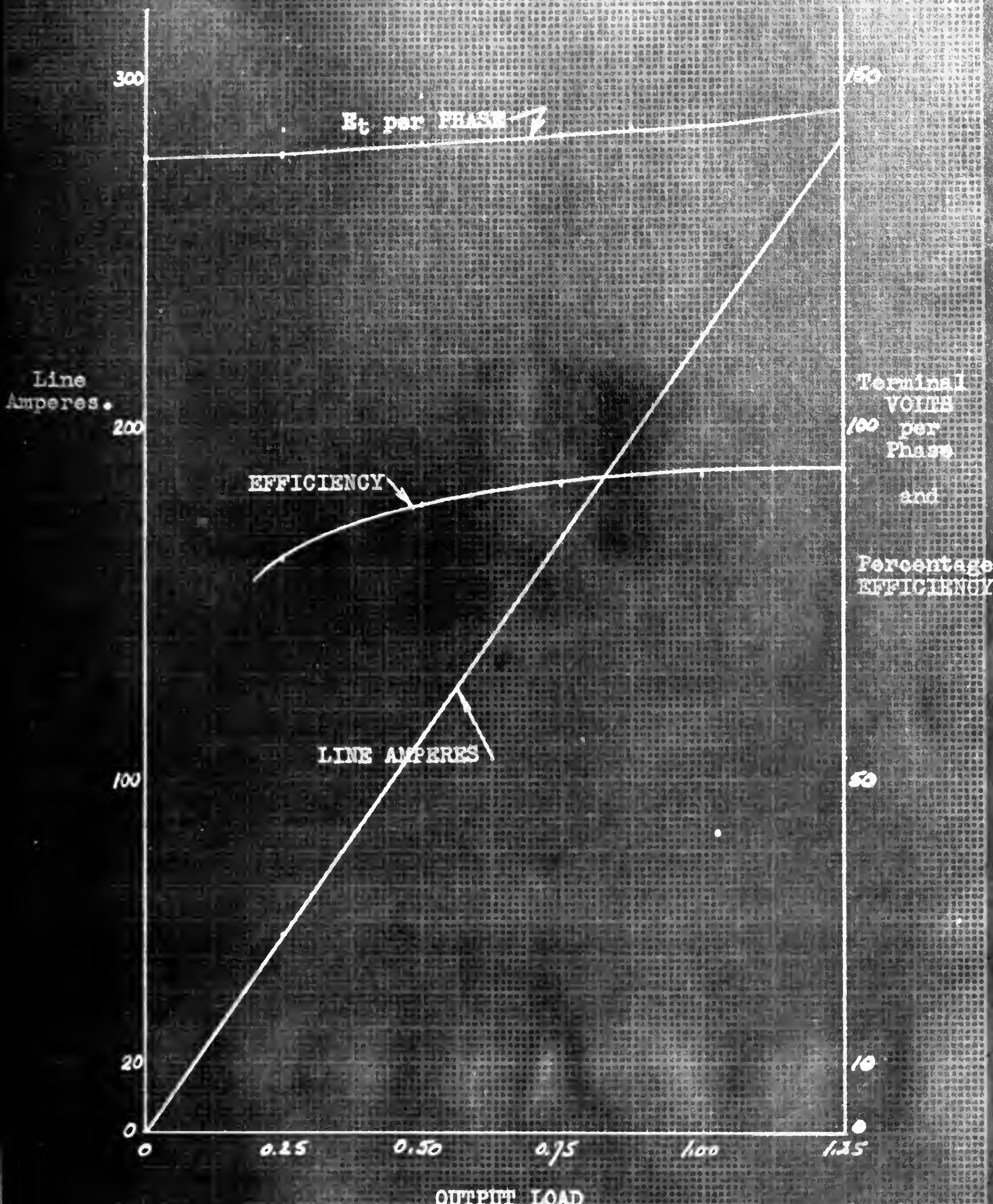


FIG 11

CALCULATION NOTES

The first page of calculations require but one detailed explanation, that of the velocity calculation for the peripheral velocity of the armature at its inner radius. We consulted the author of the sheets, Professor C. V. O. Terwilliger and accept his notation at the bottom of the sheet as suitable for our calculation if we, on assuming a ratio l_p to l, or k_3 equal to unity, make the constant before the root factor equal to the value 124, as suggested. This we did with the results noted. The specific output of our machine is a measure of the volt ampere capacity using for a measuring guide the surface area of the inner face of the armature. It is volt-amperes per square area measure. The remaining items are straight forward arithmetic.

The first item on page two of the notes is the choosing of the number of conductors per slot having approximated this value with the upper few manipulations. We, it is noted, have approximated 4.18 conductors per slot. This is impossible, and if we were to choose the number of conductors to be five, then a winding problem which would add to the complexity of the machine would result. We choose the number of conductors to be four per slot, and it proved later on this page to be satisfactory, when calculations for both the flux entering the armature per pole at full load entry and the peripheral current density entry gave results conforming with reference values for similar situations.

The insulation selections for the armature conductors has

been discussed earlier in this paper. The curves which helped determine the wire enamel thickness are taken from tabulated values of wire diameters over enamel from various wire tables found in the references. The curves appear on Figure 12. The actual data was finally taken from the GE INSULATING MATERIALS catalog of December, 1948, listed in the bibliography. The winding diagram appears as Figures 1 and 15, and the slot section to scale appears as Figure 6.

Page three of the calculations contains no startling exposure of facts that require lengthy explanation. It is a development of the armature losses, divided into core losses, tooth losses, and copper losses. The core losses have already been discussed earlier in this paper. The tooth losses follow along the same line of reasoning as the core losses. The copper losses are straight forward I^2R losses.

On page four there are several items which should be developed. First, the item of armature heating resolves in picking an empirical value for the watts dissipated per square inch of armature core area per degree Centigrade rise due to the losses found on page three. The various references select from the previous experiences of their several authors, somewhat similar magnitudes for these critical values. The better presentation of the solution appeared in those texts which segregated the value of the watts dissipated dependent upon the types of surfaces from which the losses were to be dissipated. I selected the case where the reference written by Miles Walker chose the value for the copper surfaces proper and for laminated iron surfaces. They appear in the second

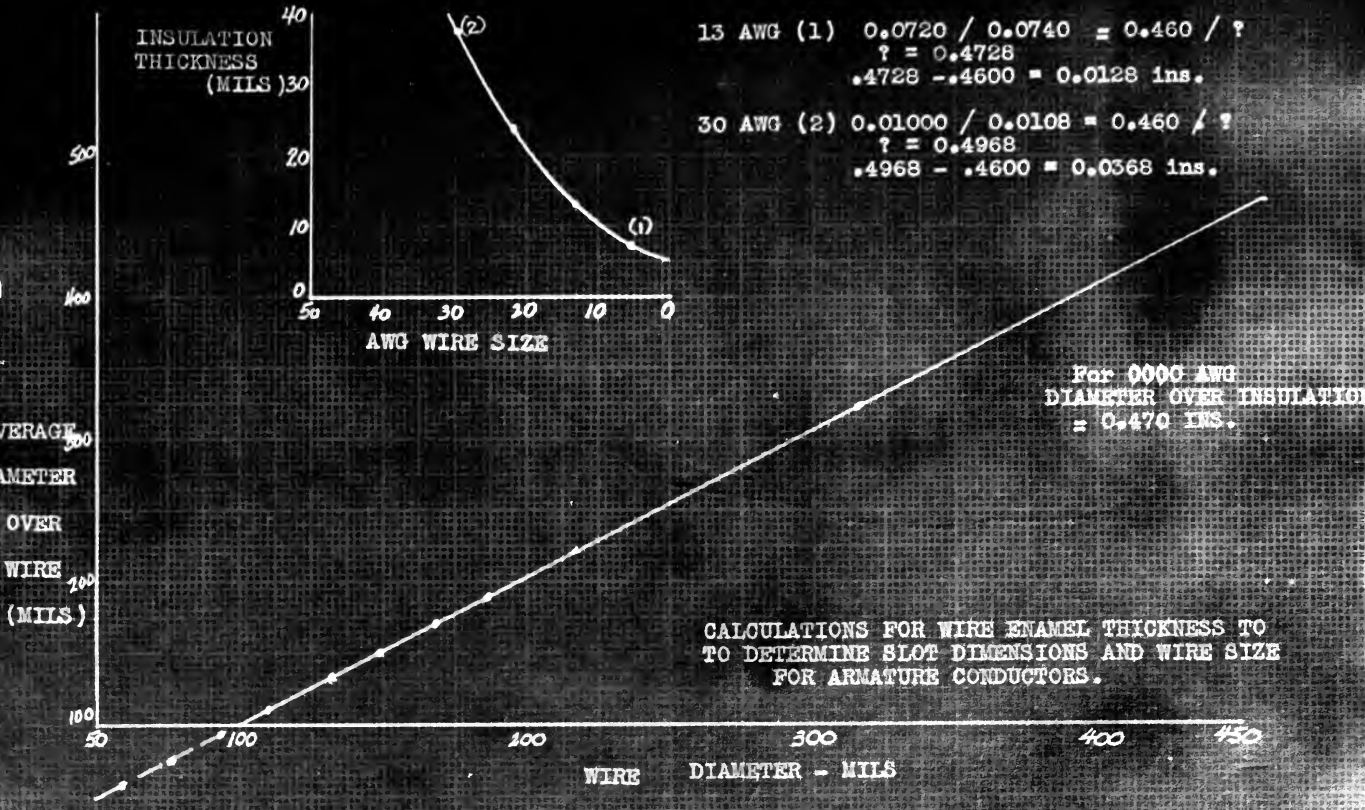

INSULATION THICKNESS (MILS)
40
30
20
10
0
50 40 30 20 10 0
AWG WIRE SIZE
(2)
(1)
13 AWG (1) 0.0720 / 0.0740 = 0.460 / ?
? = 0.4728
.4728 -.4600 = 0.0128 ins.
30 AWG (2) 0.01000 / 0.0108 = 0.460 / ?
? = 0.4968
.4968 - .4600 = 0.0368 ins.
For 0000 AWG
DIAMETER OVER INSULATION
= 0.470 INS.
AVERAGE DIAMETER OVER WIRE (MILS)
500
400
300
200
100
50 100 200 300 400 450
WIRE DIAMETER - MILS
CALCULATIONS FOR WIRE ENAMEL THICKNESS TO
TO DETERMINE SLOT DIMENSIONS AND WIRE SIZE
FOR ARMATURE CONDUCTORS.

FIG 12

(64)

item on the page four of the calculations and give rise to satisfactory results as far as our preliminary estimates and specification limitations on temperature rise due to losses were concerned.

The magnetic circuit appears as a part of the not-to-scale sketch of Figure 7. The circuit is used along with the "flux versus ampere-turns" curves for the various members of the magnetic circuit in the calculations for the number of ampere-turns for the various load voltages per phase of the generator. These values are calculated and curves made as appear in Figure 8. The tabulated calculations appear on page four of the calculations. The value of the "air-gap" ampere turns in each case are found by applying the formula furnished by the curve sheet author. This formula agrees with those of both SLICHTER and WALKER in their references to this calculation. The exact form of the formula differs in each case, and therefore, it becomes a matter of using the one thought best for this situation.

On the next page there appear a series of calculations which set the value for the minimum safe air gap required for the design. It is based upon calculations determining the air gap density, tooth fringing coefficient, ventilating duct fringing effect, all based upon the ampere-turns in the air gap and iron magnetic circuit at full load. Our calculations show 0.242 inches to be a minimum safe air gap. We are using a value of 0.25 inches, which value was based upon an estimation of STILL in his reference on the subject.

Leakage reactance calculations are based on formulae developed by Professor C. V. O. Terwilliger. They Are:

1. For the slot reactance

$$X_{SLOT} = 2\left(\frac{2\pi f}{10^8}\right)\left(\frac{3.2\,N^2}{W_s}\right)\left(\frac{8}{3}d_1 + d_2 + 4d_3 + \frac{4}{3}W_s\right) \times l_{eff} \times S \times k_{ps}$$

where X = reactance

π = 3.1416

f = frequency

N = turns per slot coil

l_{eff} = mean effective length of conductors

S = No. of slots per pole per phase

k_{ps} = pitch to slot ratio factor = $\frac{0 \times 1 + 2 \times .866}{2 \times 1} = 0.866$

2. For the tooth tip reactance:

$$X_{TOOTH\ TIP} = 2 \times \left(\frac{2\pi f}{10^8}\right) \frac{3.2 \times 4 \times N^2 \times \delta}{\left(\frac{\lambda_t}{2} + \frac{\pi W_s}{4}\right)} \times l_{eff} \times S \times k_{ps}$$

where δ = air gap

λ_t = tooth pitch

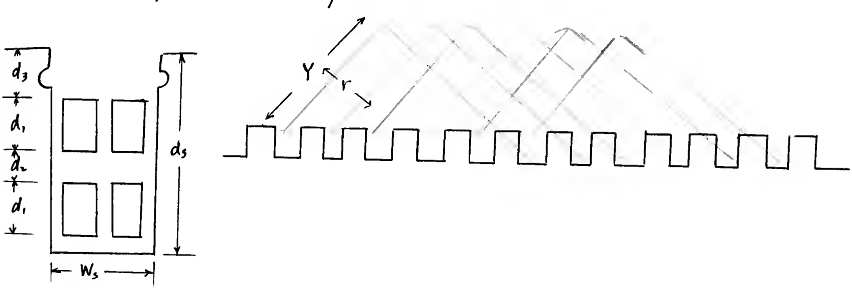
W_s = width slot

3. For the coil end leakage (external of slot)

$$X_{COIL\ ENDS} = 2 \times \left(\frac{2\pi f}{10^8}\right)(4y)\left[\frac{3.2\,N^2 S^2}{8\pi} + \frac{1.84}{\pi} S^2 N^2 \log\frac{Y}{r}\right]$$

where Y = length ½ external coil

r = radius of phase belt flux path



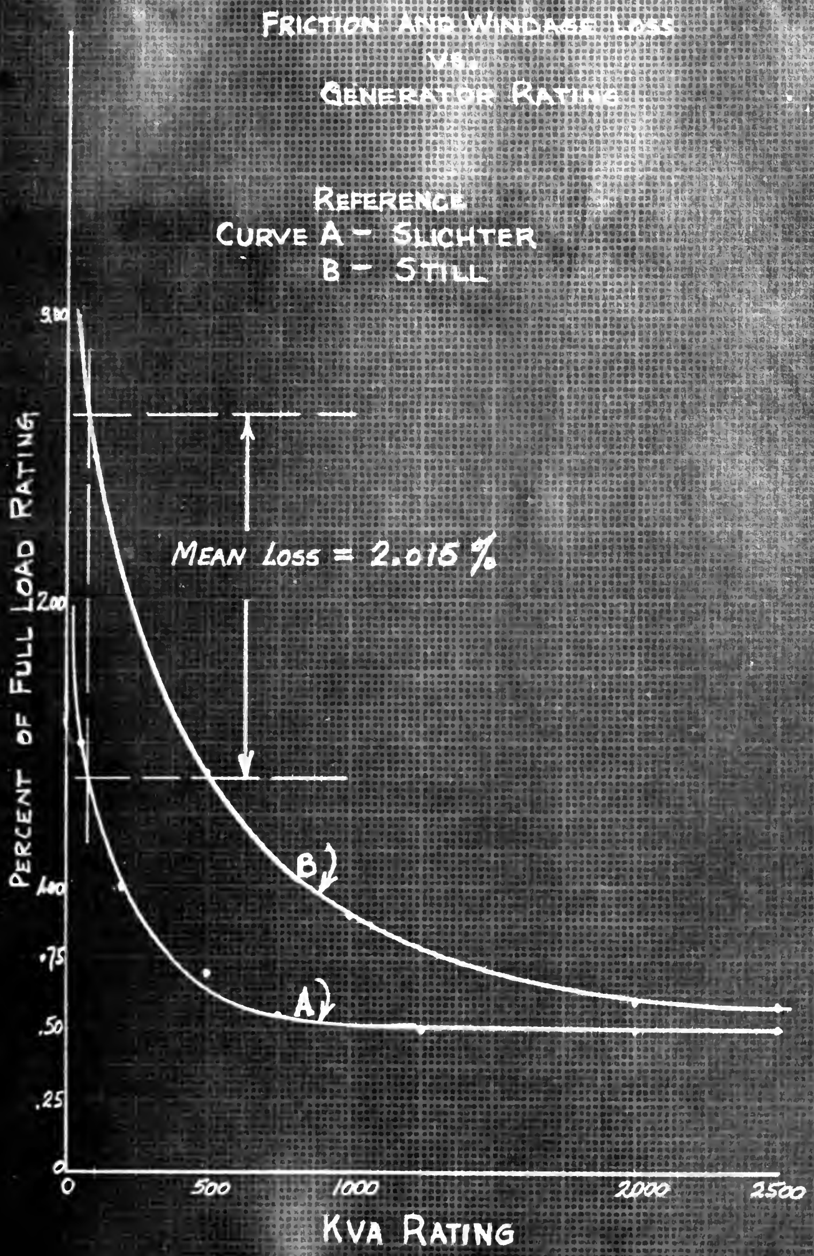
Following the formula and procedure at the lower half of page six, and graphically solving for the total field ampere turns at full KVA load as indicated in Figure 9, we arrive at values for the regulation of our machine at a non-inductive load and an 0.80 power factor load. The calculated values are in line with expected values as indicated in the references. To arrive at final regulation, we shall have to resort to the close regulation as described in the chapter on regulation and field excitation.

Field coil calculations follow along the classic lines of determining and arithmetically working out the values of ampere turns required by the field circuit to generate the output voltage, pre-selecting a field voltage, and then knowing the general dimensions of your individual field pole core, selecting the size wire and length required, thereby determining the number of field turns, and then selecting the arrangement whereby they will be fitted to their alloted space. Checks such as appear on this page guide the calculator.

Field circuit thermal calculations then are worked out and combined with the armature thermal calculations previously determined. The two then determine the overall thermal picture.

Finally, efficiency calculations are carried out utilizing the data of Figures 13 and 14. Weights and costs of armature iron and copper are then determined to give a general overall picture of the machine on paper.

To round out the design, certain mechanical calculations are made as follows:



FRICTION AND WINDAGE LOSS
VS.
GENERATOR RATING
REFERENCE
CURVE A — SLICHTER
B — STILL
MEAN LOSS = 2.015 %
PERCENT OF FULL LOAD RATING
3.00
2.00
1.00
.75
.50
.25
0
500
1000
2000
2500
A
B
KVA RATING

FIG. 13

TERMINAL VOLTS PER PHASE
VS.
% OF GENERATOR LOADS
AT
0.80 POWER FACTOR

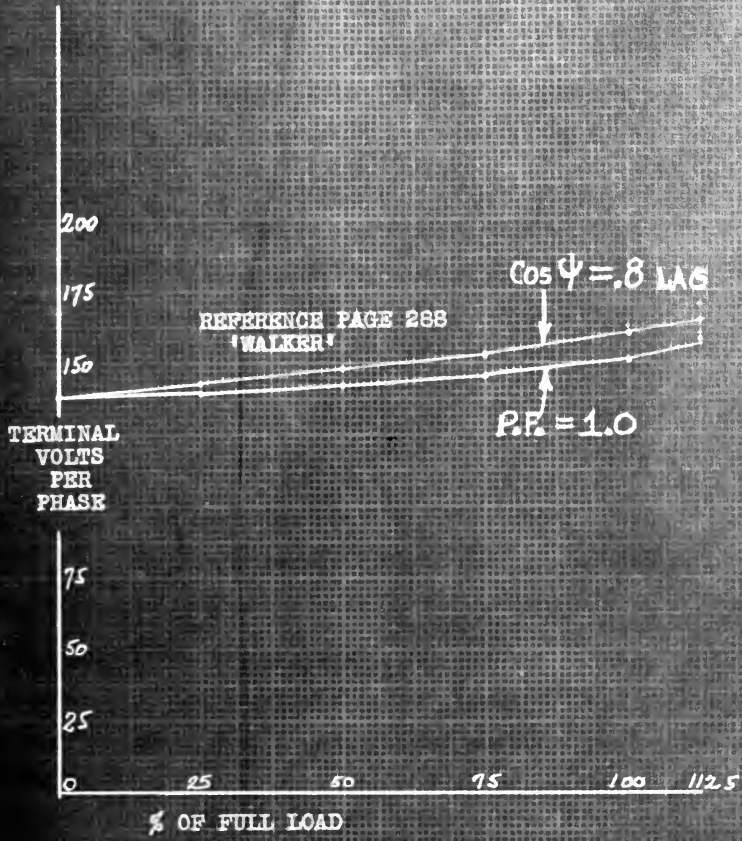


FIG. 14

1. The average force tending to displace the coils in a slot $= F_s = \dfrac{T \ \ell \ I \ B_{max}}{2 \times 10 \times 444{,}800}$

$$= \frac{2 \times (4.7 \times 2.54) \times (225.5 \times 1.25) \times 118{,}200}{8{,}896{,}000}$$

$= 91$ pounds

where T is the number of turns per coil side,

ℓ is the length of the wire in cms.,

I is the current in the wire in amperes,

B_{max} is the density of magnetic field,

10 is a conversion factor for amperes to absolute units and 444,800 is the number of dynes per pound force.

2. The diameter of the rotor shaft $= D_r =$

$$= \sqrt[3]{\frac{\text{watts, full load}}{\text{r.p.m. of machine}} \times (0.84)^3} =$$

$= 0.84 \times 5.920$

$= 4.97$ inches, and we shall use 5.00 inches

3. From Page 560 in STILL, the journal diameter needs be but 40% the shaft diameter, or 2.00 inches, and the journal length about 2-3/4 x D_r, the shaft diameter. Our bearing loading will be less than these dimensions can sustain. Therefore, we shall pick a single row, radial thrust bearing of 2.00 inch diameter, and, as indicated in the S.A.E. standards for radial and angular ball and roller bearings, the width of this bearing will be approximately 1.25 inches. It will have a radial capacity of approximately 2500 psi and a thrust capacity of one half that figure, adequate for our situation.

4. The centrifugal force exerted on the field pole bolts equals $F_c = 0.000341 \times W \times R \times (RPM)^2$ psi

$$= 0.000341 \times 20 \times 1 \times (360)^2$$

$$= 880 \text{ psi}$$

where W is the weight, in pounds, per pole,
R is the radius in feet, to the pole base,
and RPM is the revolutions per minute of the pole about the machine axis.

Since each mild steel bolt can withstand 15,000 psi tensile stress, we can limit our tie down bolts to one in number for each pole. They shall have to be rust resistant either as a result of coating or material, and shall have to be of a material close to the silicon steel of the pole pieces in the electromotice series to reduce any galvanic action between the surfaces of contact.

5. The mechanical stress at the root of the pole piece is a summation of the centrifugal force exerted on the pole piece and the distortion force acting on the pole. The former we have calculated to be 880 psi. The distortion force equals $F_d = \dfrac{B^2 A}{8\pi}$ dynes or $\dfrac{B^2}{72 \times 10^6}$ psi

$$= \frac{\left[38000 \times 2.54^2\right]^2}{72 \times 10^6}$$

$$= 840 \text{ psi}$$

Vector summation of these two forces results in a force at the pole root of approximately $880 \times (2)^{\frac{1}{2}}$ or 1250 psi. The pole material is capable of withstanding a bending stress of approximately 16,000 psi, and so there is an adequate safety factor involved in this instance.

6. Fly wheel section, where "fly wheel" means the pole carrying rim, may be determined by calculating the stresses set up in the rim itself and then, knowing the allowable stress of the rim material and utilizing an adequate safety factor, a rim section may be selected. The one known dimension of the rim section is that it should be at least as long axially as the pole it supports.

The force, P, exerted on the rim, is determined by a formula similar to that used for the centrifugal force exerted on the pole pieces themselves, i.e.

$$P = 0.000341 \times W \times R \times (RPM)^2$$

$$= 0.000341 \times x\ 100 \times 23/24 \times (360)^2$$

$$= 675 \text{ psi}$$

The rim material is capable of sustaining a centrifugal force of approximately 15,000 psi, therefore, a section of very small thickness may be employed. The factor of fabricating such a section comes into play at this point, and so a selection of one inch thickness was made for fabricating reasons only, and the factor of safety increases greatly accordingly.

7. The tension in the flywheel due to carrying 20 poles is increased in proportion to the weights of the poles and the revolutions per minute of the system. This tension is easily determined, and is located in the outer rim of the flywheel. It is:

$$P_t = P + \frac{pP}{2\pi} \text{ psi.}$$

$$= 675\left(1 + \frac{10}{\pi}\right)$$

$$= 2820 \text{ p.s.i.}$$

This figure is still well within the limits of stress allowable and carries with it a factor of safety of greater than five.

8. From FINK, critical speed is the ratio of the empirical constant 200 to the square root of the deflection of the shaft. The deflection of a uniformly loaded shaft depends upon the shaft length, diameter, and mass of the rotor and attached weights it carries.

$$\text{deflection} = \frac{P l^3}{48 E J}$$

where E, for steel shafting, is 30×10^6, and

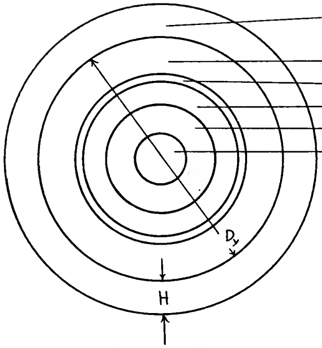
J is $\frac{1}{2} W r^2$

deflection becomes $360 \times 20^3 \div 48 \times 30 \times 10^6 \times \text{pi} \times 2.5^2 \times 0.14$

and equals 0.000116 inches.

Critical speed then becomes $200 \div (0.000116)^{\frac{1}{2}}$, or 18,600 RPM, approximately. This is beyond our wildest imagination, and so we shall not discuss it further.

9. We shall use non-magnetic steel end bells and armature yoke structure steel in order to reduce end coil leakage losses.



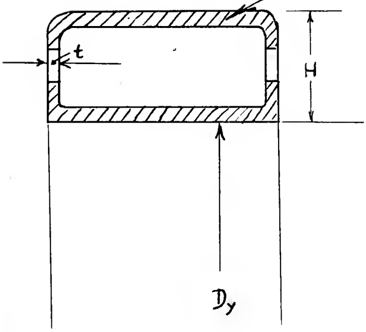
$H = 1.5 + D_y/12$ inches

D_y = [illegible] inches

= [illegible] inches

$H = 1.5 + 4$[illegible]$.5/12$ = [illegible]5 inches

Therefore, OD of arm. yoke = [illegible] inches, approx.



armature pole section, t,

= empirically,

= 0.[illegible] + $0.01 \times D_y$

= 0.[illegible] + $0.01 \times$ [illegible]

= 0.375 inches

This completes the more important of the mechanical calculations which determine the overall dimensions and weights of the machine. The minor details, such as selecting the bearing number, the size and type of bolts required, the drill and tap dimensions for fitting the bolts, and other numerous detailing, is beyond the scope of this paper. They are details for the planning section. Figures representing a preliminary set-up for the draftsman and planners are included as Figures 15 and 16.

This completes this paper. We have computed the necessary dimensions for an alternator which will meet the specification. We do not claim that they will work to give the rated output at the power factor but feel confident that there are no arithmetical mistakes and that the assumptions are within all known reason. Tests are the only method which will, in our minds, prove that the machine will operate. This is beyond our province at this time.

Major theory behind the calculations are discussed within the paper. Major calculations are worked out in the Appendix. The illustrations represent the results, and give an idea of the construction and size of various parts of the machine. We hope that this meets the requirement of the specification.

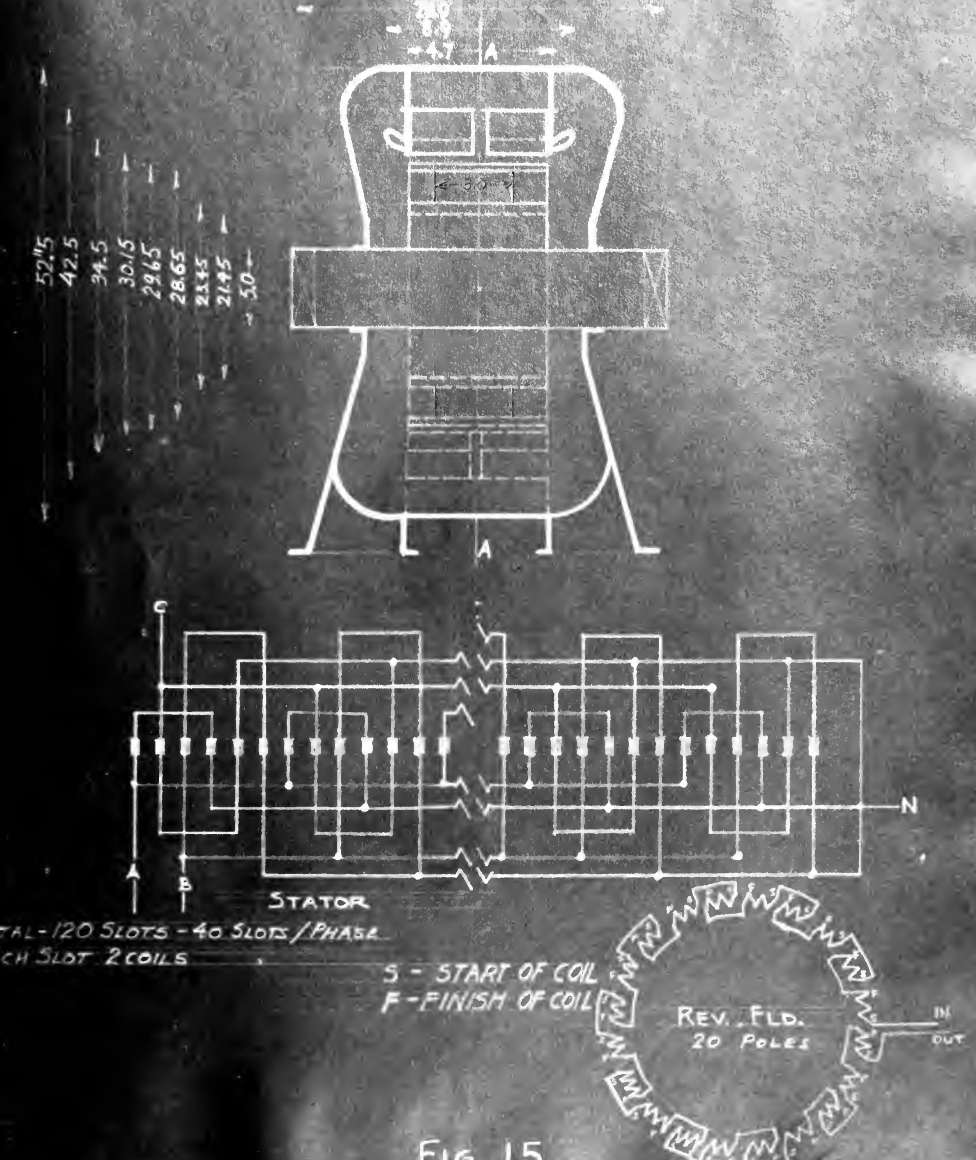
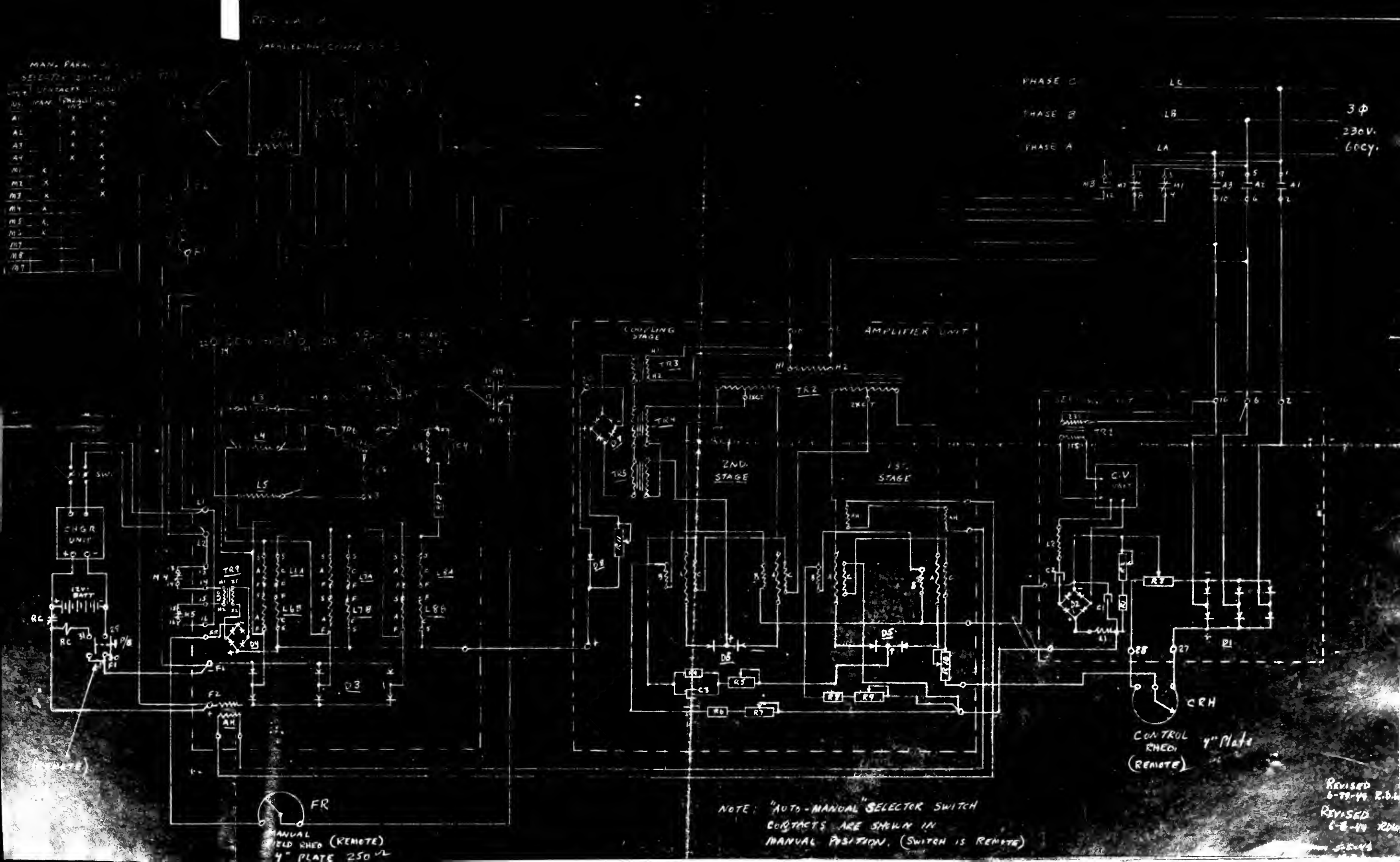

52.5
42.5
34.5
30.15
29.65
28.65
23.45
21.45
5.0
4.7
3.0
A
A
C
A
B
N
STATOR
TAL-120 SLOTS - 40 SLOTS / PHASE
CH SLOT 2 COILS
S - START OF COIL
F - FINISH OF COIL
REV. FLD.
20 POLES
IN
OUT

FIG. 15


PHASE C
PHASE B
PHASE A
LC
LB
LA
3 Φ
230V.
60cy.
AMPLIFIER UNIT
COUPLING STAGE
TR3
TR2
TR4
TR5
2ND. STAGE
1ST. STAGE
C.V. UNIT
TR1
D2
D5
D6
D3
D4
D8
R8
R7
R6
R5
R9
R10
R11
C3
L5
L4
L3
TR9
AH
ENGR UNIT
12V. BATT
RC
P/B
SW
F1
F2
CRH
CONTROL RHEO. (REMOTE)
4" Plate
FR
MANUAL FIELD RHEO (REMOTE)
4" PLATE 250 Ω
NOTE: "AUTO-MANUAL" SELECTOR SWITCH CONTACTS ARE SHOWN IN MANUAL POSITION. (SWITCH IS REMOTE)
REVISED 6-29-44
REVISED 6-8-44

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Thesis 13114
S27 Scharfenstein
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